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Evaluation of Municipal Solid Waste Landfill Cover Designs

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16. ABSTRACT

The HELP (Hydrologic Evaluation of Landfill Performance) Model was used to evaluate the hydrologic behavior of a series of one-, two-, and three layer cover designs for municipal solid waste landfills with climatic conditions for 10 U.S. cities. The specific landfill cover designs were chosen to isolate the effects of features such as surface vegetation, thickness, soil type and hydraulic conductivity of the layers on the average annual runoff, cover percolation, evapotranspiration, and lateral drainage. The results of the evaluations are presented in numerous bar charts to supplement the tables and schematics. Soil hydraulic conductivity was one of the most important design features in controlling cover percolation for all covers tested. Minimal cover percolation and runoff were the two main criteria used to select the four best cover designs, which are described under Results and Discussion. The report also includes a brief discussion of four other aspects of landfill cover design; animal and vector control, subsidence, gas control, and cost.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of state and local governments and the needs of both large and small businesses in handling their wastes responsibly and economically.

This document presents an evaluation of the effect of various design parameters on the hydrologic behavior of municipal solid waste landfill covers under a range of climatic conditions. The evaluation was conducted using the HELP (Hydrologic Evaluation of Landfill Performance) Model. Also included are brief discussions of animal and vector control, subsidence, gas control and costs of municipal solid waste landfill covers. This document is intended for designers of landfill covers, HELP Model users, and others interested in the performance of landfill covers. For further information, please contact the Land Pollution Control Division of the Hazardous Waste Engineering Research Laboratory.

Thomas R. Hauser, Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

This report evaluates the hydrologic performance of a variety of layered cover designs for municipal solid waste landfills. The evaluations were made using the HELP (Hydrologic Evaluation of Landfill Performance) Model, a computer model developed for the U.S. Environmental Protection Agency. The study examines the sensitivity of the hydrologic "outputs" of a landfill cover (runoff, evapotranspiration, lateral drainage, and cover percolation) to various components of the cover itself, including surface vegetation, the thickness, soil type, and hydraulic conductivity of the various layers, and the slope and spacing of the drainage tiles in the drainage layer. The various cover designs were tested (using the HELP Model) for 10 different U.S. cities with a wide range of climates. The results of the evaluations are presented graphically.

Three general types of cover designs were tested: one-layer, two-layer and three-layer designs. For the one-layer type covers, cover percolation is reduced as the soil type of the cover ranges from coarse-textured (sandy) soils to fine-textured (clayey) soils. Cover percolation for one-layer covers using a clay-loam soil is less than 5 inches at 4 cities where average annual precipitation is less than 33 inches (Denver, San Francisco, Corpus Christi, and Milwaukee).

For two-layer covers consisting of a 6 inch gravel layer over a clay barrier, cover percolation is less than 1.7 inches

for all 10 cities tested. Runoff is relatively high for this type, ranging from 1.6 to 24 inches for the 10 cities.

For two-layer covers consisting of a topsoil layer over a clay barrier, cover percolation is slightly reduced as the soil texture of the topsoil layer is reduced from coarse to fine. Cover percolation is increased by 0.6 to 0.8 inches when the thickness of the clay barrier layer is reduced from 24 to 12 inches. Cover percolation is reduced by approximately a factor of 10 when the hydraulic conductivity of the barrier layer is reduced by a factor of 10. The HELP Model results indicate that these cover types experience periodic saturation of the topsoil layer during the periods of record for the 10 cities tested (10 to 20 years). This condition could be harmful to the vegetative cover and could result in excessive surface runoff, depending on the frequency and persistence with which saturation occurs under a particular climatic regime. Further investigation of this phenomenon would be necessary to determine the suitability of these cover types for a given climate.

For three-layer covers consisting of a topsoil layer, a drainage layer, and a clay barrier, cover percolation is reduced by 0.25 to 0.55 inches when clay loam instead of sandy loam is used in the topsoil layer. Reducing the hydraulic conductivity of the drainage layer by a factor of 8.4 results in an increase in cover percolation ranging from 0.5 to 0.9 inches for the 10 cities. Results for Lexington, Kentucky indicate that cover percolation is reduced by 3 to 5 percent for every 1 percent increase in the slope of the drainage layer; and that cover percolation is reduced by 3 to 9 percent for every 25 foot decrease in drainage spacing, as the spacing ranges from 200 to 25 feet. Reducing the hydraulic conductivity of the barrier layer by a factor of 10 significantly reduces cover percolation. The amount of the reduction depends on the initial value of the hydraulic conductivity and the precipitation at the site. For most of the two and three layer cover designs examined in this study, a given level of cover percolation can be achieved by adjusting the hydraulic conductivity of the barrier layer.

Four cover designs that demonstrated good hydrologic performance also were evaluated in terms of vector and animal control, gas control, resistance to subsidence, and cost.

This report can be used to assist in the design of a municipal solid waste landfill cover for a particular location. It helps identify how the various components of a cover design affect its hydrologic behavior.

This report was submitted in fulfillment of Contract No. 68-03-3248, Work Assignment No. 5, under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from August, 1985 to August, 1986 and work was completed as of August, 1986.

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SECTION 1

OBJECTIVE OF STUDY

The purpose of this project is to evaluate the performance of various types of municipal solid waste landfill cover designs. Hydrologic performance is evaluated using the HELP (Hydrologic Evaluation of Landfill Performance) Model (Schroeder et al., 1984a). Performance related to other factors (cost,subsidence, gas emissions control, vector control) is based on a subjective evaluation using available information.

A series of landfill cover designs was developed to be used in the evaluation process. The designs were developed to correspond with the input requirements of the HELP Model.

The HELP Model was developed by the U.S. Army Engineer Waterways Experiment Station for the Environmental Protection Agency, to estimate the amounts of surface runoff, subsurface drainage, and leachate resulting from the operation of a wide variety of possible landfill designs. The hydrologic performance of a landfill design with up to nine different layers can be modeled. Input parameters include type of layer, surface vegetation, thickness and soil type of each layer, and slope and drain spacing in the drainage layer. Site-specific precipitation and temperature data can also be entered in the model, or default climatic data for a number of cities can be used. Default data refers to data that is supplied by the computer program. For a detailed explanation of the HELP Model, the reader should refer to Schroeder et al., 1984a and 1984b.

The HELP Model allows the user to specify the layers in a landfill design as one of 5 types: (1) vertical percolation (VP); (2) lateral drainage (LD); (3) barrier (B); (4) waste; or (5) barrier with an impermeable liner. A typical landfill cover design is shown in Figure 1. A brief description of the layer types follows.

A vertical percolation (VP) layer allows vertical flow only. Water can percolate downward, or move upward and be lost by evapotranspiration. A VP layer is generally located at the top of the landfill cover to protect the lower layers and provide a medium for vegetative growth. This layer is usually moderately permeable. A lateral drainage (LD) layer is designed to intercept water percolating from the surface, and collect it by means of a network of perforated pipe or drainage tile embedded in the layer. This layer will usually be composed of a highly permeable material such as sand or gravel. The top of the underlying layer is sloped to facilitate drainage toward the tiles. The HELP Model allows for slopes ranging from 0 to 10 per cent, and spacing of drainage tiles 25 feet or more apart. The model allows both vertical and lateral flow in the LD layer. The HELP Model requires that slope and spacing of a drainage tile network be specified for a lateral drainage layer. A drainage layer without tiles can be simulated by making the value for spacing sufficiently large.

A barrier layer is designed to minimize vertical percolation

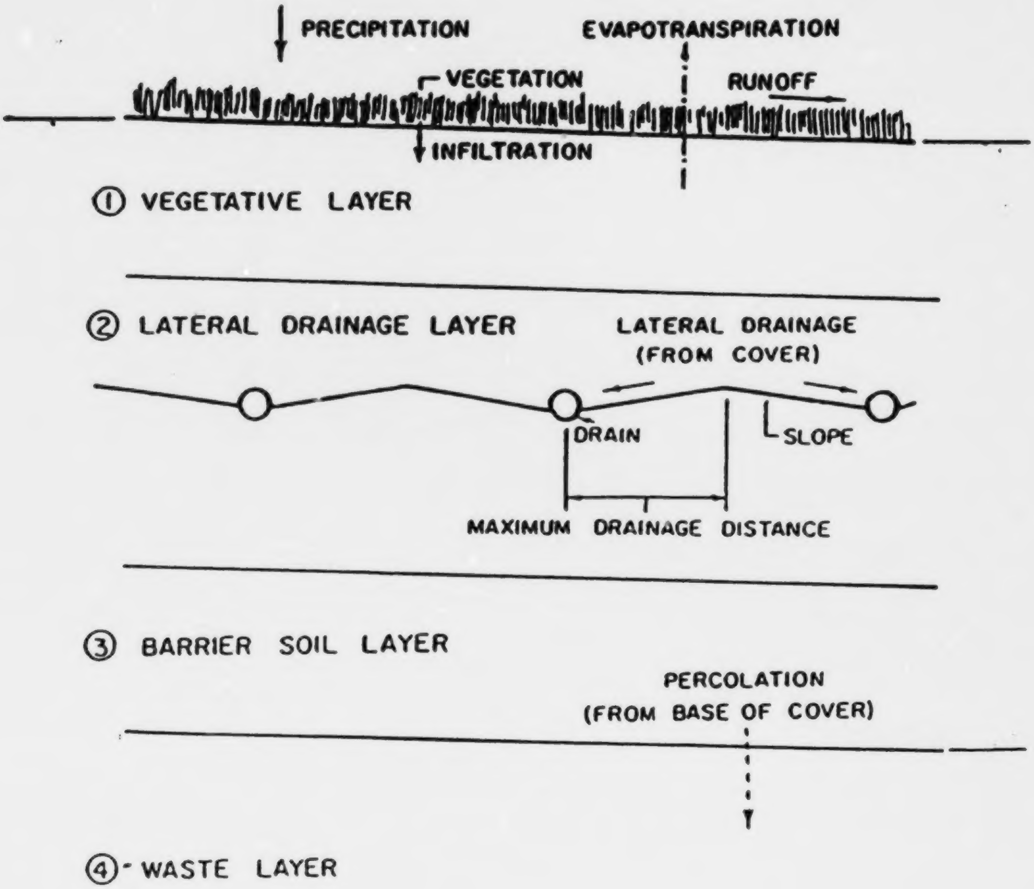

PRECIPITATION
EVAPOTRANSPIRATION
VEGETATION
RUNOFF
INFILTRATION
① VEGETATIVE LAYER
② LATERAL DRAINAGE LAYER
LATERAL DRAINAGE (FROM COVER)
DRAIN
SLOPE
MAXIMUM DRAINAGE DISTANCE
③ BARRIER SOIL LAYER
PERCOLATION (FROM BASE OF COVER)
④ WASTE LAYER

FIGURE 1. Typical Landfill Cover Profile (Adapted from Schroeder et al. 1984a)

designed to prevent any water from reaching the underlying waste layer, where it could become contaminated. A barrier layer in the liner (beneath the waste layer) is designed to prevent leachate from leaving the landfill and contaminating the groundwater. A barrier layer is usually constructed of material with a low hydraulic conductivity such as compacted clay. The HELP Model allows only vertical flow in a barrier layer.

A waste layer represents the refuse material stored in the landfill, and allows only vertical movement of water.

A barrier layer with an impermeable membrane is similar to the barrier layer mentioned above, except that it also includes a synthetic liner directly above the barrier. The user must specify the leakage fraction for the membrane.

A basic water balance equation which gives a simplified explanation of how the HELP Model simulates hydrologic behavior of a landfill cover is: Precipitation = Surface Storage (Snow) + Runoff + Surface Evaporation + Evapotranspiration + Subsurface Lateral Drainage + Cover Percolation + Stored Soil Moisture. The daily precipitation at a landfill site is the "input" to the landfill cover. The terms on the right side of the equation are the daily "outputs" of the landfill cover. For the HELP Model runs used in this report, "summary" output of each run was obtained. This means that all terms in the water balance equation are expressed as the average annual values for the period of record. For this type of output, the water balance equation can be expressed more simply as: Precipitation = Runoff + Evapotranspiration) + Lateral Drainage + Cover Percolation, since the other terms in the water balance become relatively insignificant when average annual values are used.

Runoff consists of surface water which leaves the surface of the landfill without infiltrating the soil surface. Evapotranspiration is that portion of the input precipitation which leaves the landfill as water vapor due to evaporation from the soil or transpiration by vegetation. Lateral drainage is water which has infiltrated the soil surface, and which flows horizontally until it is collected by the drainage system. Lateral drainage is produced only in cover designs that have a lateral drainage layer. Cover percolation is water that percolates vertically through all layers of the cover, and eventually flows out the bottom. For a more complete description of the water balance used in the HELP Model, see Schroeder et al., 1984a and 1984b.

The cover designs tested in this study are based on the assumption that the prime objective of a landfill cover design is to minimize the amount of cover percolation produced, since this water will percolate through the waste layer directly below the cover, where it can pick up contaminants. A good design of this type should also minimize and control runoff, to prevent erosion of the cover, and should maximize evapotranspiration. Lateral drainage must be collected and disposed of by a system of drainage pipes or tiles and a pumping or other disposal system.

Precipitation intensity and the duration of individual storms, as well as the average annual precipitation, are important in determining the hydrologic performance of landfill cover designs. High intensity rainfall of sufficient duration can cause saturation of the surface VP layer, leading to increased runoff and erosion potential, and possible harm to vegetation due to flooding of the root zone. The parameter in the HELP Model summary output that indicates possible problems with saturation of the VP layer is the "maximum daily head". This is the maximum head of water above the top of the barrier layer that exists at the end of the day for the period of record. In evaluating an actual cover design, it is advisable to obtain a daily or monthly output from the HELP Model to determine the daily heads above the barrier layer over an extended period. This is to ensure that the lateral drainage layer is performing satisfactorily, and that repeated saturation is not occurring. For the cover designs tested for this study, the maximum daily head for the period of record is shown in the HELP Model data in Appendix B. Also shown is the maximum saturation depth for each cover type. This is the combined thickness of the VP and LD layers overlying the barrier. A maximum daily head equal to or greater than the maximum saturation depth indicates that saturation of the soil profile above the barrier has occurred.

When saturation of the VP layer occurs frequently for a cover design being run on the HELP Model, the amount of annual runoff is greatly increased. This situation occurs for some of the two layer cover designs tested in this study. Examples of this are Types C1b and C1c. (See Section 3 and also Figure 13.)

It should be noted that covers can also be designed to achieve a different objective: to deliberately allow a certain amount of water to percolate through the cover into the waste layer. Under this system, leachate from the waste layer is collected by a drainage system below the waste and recirculated through the waste layer. The idea is to increase the rate of decomposition in the waste layer by promoting bacterial activity, thus reducing the time period necessary for the waste material to reach chemical, physical, and biological stability. More information on this type of cover design strategy can be found in Barber and Maris (1984), Lu et al.(1984), Pohland (1976), and U.S.EPA (1985).

SECTION 2

CONCLUSIONS

The results presented in this report describing the effects of various design parameters on the hydrologic performance of landfill covers are predictions based on a computer model, and should not be interpreted as absolute predictions of landfill cover behavior. They are intended to help the reader determine the relative importance of various design parameters in terms of their effect on hydrologic performance, for a range of climates. They also provide a comparison of the hydrologic performance of various types of one-, two-, and three-layer covers.

This report analyzes the hydrologic behavior of landfill cover designs solely in terms of average annual values of cover percolation, runoff, evapotranspiration, and lateral drainage for each design. Although the performance of a cover design during individual design storm events is also important, this type of analysis was beyond the scope of this report. The reader should note that the HELP Model can be used to analyze the daily water balance of a cover design, employing user-supplied daily precipitation data.

For one-layer cover designs, the hydraulic conductivity of the single layer, as determined by soil type and degree of compaction, is the most important design feature in controlling cover percolation. For two and three layer covers which include a barrier layer, the hydraulic conductivity of the barrier is the single most important parameter in controlling cover percolation.

Three-layer covers that include a drainage layer generally result in lower cover percolation than one or two-layer covers.

For most of the two and three layer cover designs examined in this study, a given level of cover percolation can be achieved by adjusting the hydraulic conductivity of the barrier layer.

The results of this study show that they hydrologic behavior of the same landfill cover design can vary significantly for different climates.

A complete summary of the effect of design parameters on hydrologic performance is given in Section 7, Summary of Results. For detailed information on the effect of design parameters under different climate conditions, the reader should refer to Sections 1, 4, and 5 of this report.

In designing a landfill cover, objectives for the design, such as the maximum amounts of cover percolation and runoff, and the amount and frequency of VP layer saturation that are acceptable, should first be established. These objectives are based on such factors as: the type of waste to be stored in the landfill; the type of liner beneath the waste layer; geological conditions in the vicinity; the design storm that the cover is intended to withstand; the local climatic regime; the potential threat of groundwater contamination; proximity to aquifers, residential areas, or wildlife habitat; and budget constraints.

Section 3 presents four recommended cover designs which demonstrate good hydrologic performance, according to the HELP Model. These four designs are examples of cover types which may be satisfactory for certain applications, and are intended to provide an example of how the results of this study might be applied. They are also the basis for analyzing the other factors in cover design addressed in this report: vector control, gas control, subsidence, and cost.

Three types of animals and vectors which can cause problems at landfills are birds, burrowing animals (such as rats), and insects. Birds are controlled by insuring that the landfill cover is sufficiently thick and compacted to prevent digging. Burrowing animals are controlled by incorporating a layer of material with low shear or tensile strength (such as sand or gravel) to discourage tunneling. Insects are controlled by a layer of compacted soil at least 6 inches thick, and by grading to prevent ponding of water on the cover surface.

Techniques for controlling subsidence of landfill covers are still being developed, and can be divided into two categories: (1) operations performed to control subsidence in the waste layer and (2) features of the cover layer which are intended to minimize the effects of subsidence. Examples of the first method are increasing the ratio of daily soil cover to waste, and compaction. An example of the second is the creation of a stable foundation or buffer layer between the base of the cover and the waste layer, consisting of 24 inches or more of compacted sand or gravel.

Techniques for gas control depend on the type, amount, and distribution of gas production in the landfill. A variety of technologies have been used, depending on site-specific factors. Some of these are discussed briefly in Section 6 of this report.

The reader is referred to the references in the Bibliography for more detailed information.

Approximate cost information is presented in Section 6 and Appendix C for the four recommended cover types, based on a conceptual design for a 10 hectare landfill cover and mid-1980 estimates. The data indicate that the most expensive items in cover design are the installation and materials costs for soil materials (such as topsoil, sand and gravel), and the synthetic membrane, if one is used.

The findings from this study should provide useful guidelines for designing a cover for a specific landfill site in a particular climatic regime.

SECTION 3

RECOMMENDED COVERS

Based on the results of the HELP Model runs, several cover types can be recommended on the basis of their hydrologic performance. The recommendations presented here are based on minimizing cover percolation and runoff.

These recommendations are designed to point the way to possible cover designs which may be satisfactory for certain applications. The design of a cover for an actual site must take into account site-specific conditions, as well as other important factors in landfill design, such as cost, vector control, subsidence, and gas control. A brief discussion of these factors is included elsewhere in this report.

Type B1c, of the one layer cover types, performed well in Denver, in terms of cover percolation and runoff produced. This cover type is recommended for use in arid climates (15 inches or less annual precipitation), at sites where hazardous materials are not a problem (for example, at a small town municipal landfill), and where a relatively low cost cover is desired. This cover resulted in less than 5 inches of cover percolation at 3 other cities (San Francisco, Corpus Christi, and Milwaukee) where average annual precipitation is less than 33 inches. It may be acceptable at similar sites, depending on the maximum amount of cover percolation that is allowable. The capability of this cover design to perform satisfactorily will depend on the capability of the soil selected to support vegetation, resist surface erosion, and minimize infiltration into the soil surface.

Type A1, a two layer cover, performed relatively well at all locations. The main problem with this cover type would be handling the large amounts of runoff generated in humid climates, or during short, intense storm events. While it is true that the gravel surface layer would be relatively resistent to erosion, the runoff would have to be disposed of after it left the surface of the landfill. Another concern with this design is the relatively thin surface gravel layer. This makes it more difficult to maintain a uniform thickness of this layer during construction and other activities which require vehicles on the surface. Also, the clay barrier layer would be subject to drying and cracking due to the shallow depth and porosity of the over-lying gravel layer. The latter could be prevented by using a membrane over the clay layer to reduce dessication, prevent erosion of the clay layer by subsurface drainage in the gravel layer, discourage plant growth, and reduce percolation.

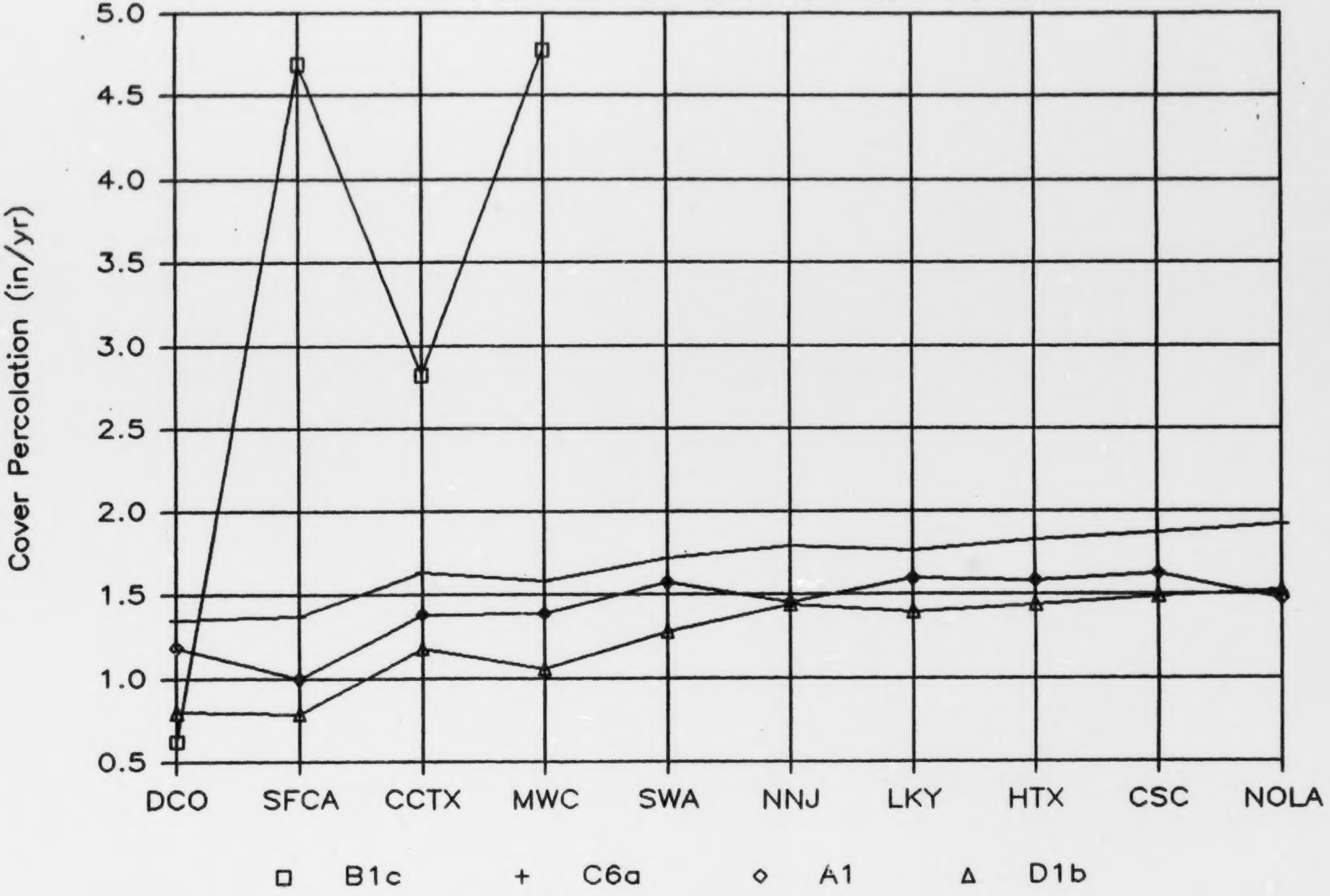
Type C1c, of the two-layer cover types, performed well in Denver. Its performance was very similar to that of Type B1c. It provides an extra margin of safety over the B1c design because of the presence of the barrier layer. However, it would also be more expensive. The same restrictions apply that were cited above for Type B1c.

Type C6a, a two-layer cover type with drains in the upper layer, performed fairly well at locations with 42 inches or less of annual precipitation.

The three-layer cover designs are the best overall designs in terms of minimizing cover percolation and runoff. For the VP layer, 24 inches of topsoil in the sandy loam to clay loam range is recommended. A high plant available water capacity is desirable to maximize evapotranspiration. Ability to support a good stand of vegetation is important. The LD layer should be at least 12 inches thick with a high hydraulic conductivity (greater than 6 inches per hour) and a moderate slope (between 3 and 6 percent). Type D1b is an example of a 3 layer cover which demonstrates good hydrologic performance.

Figure 2 compares cover percolation for Cover Types A1, B1c, C6a, and D1b. These types are used in the remainder of the report to evaluate performance of covers in terms of vector control, gas control, subsidence and cost.

FIGURE 2



Cover Percolation Comparison

Recommended Covers: A1, B1c, C6a, D1b

SECTION 4

BASIC COVER DESIGNS

Four basic cover designs, Type B1, Type A, Type C and Type D, were evaluated using the HELP Model. Different design elements were varied to develop a series of cover types within each basic design. The specifications for all types used are shown in Appendix A.

Basic design B1 is a one-layer cover, consisting of a single vertical percolation layer.

Basic design A is a two-layer cover, consisting of a gravel vertical percolation layer and a barrier layer.

Basic design C is subdivided into two categories. The first category consists of cover types C1, C2, C3, and C5, which are two layer covers consisting of a vertical percolation layer and a barrier layer. The second category consists of cover types C4 and C6, which are an attempt to model a continuous topsoil layer, with both vertical and lateral drainage, over a barrier layer. The topsoil layer is modeled as a VP layer and an LD layer composed of the same soil type, because the HELP Model does not allow for lateral flow in a vertical percolation layer. The thickness of the vertical percolation layer for Types C4 and C6 is equal to the evapotranspiration depth for the vegetation type used. This is because the HELP Model allows evapotranspiration only in a vertical percolation layer, and only within the ET depth specified in the input parameters. The thickness of the lateral drainage layer is equal to 24 inches (for type C4) or 36 inches (for type C6), minus the thickness of the vertical percolation layer.

The C4, C5, and C6 designs provide a means for evaluating designs where the same soil material is used in both the surface VP layer and the LD layer. These designs might provide a means of reducing costs, by eliminating the need to use sand or gravel for the lateral drainage layer where a suitable soil material is locally available. (See "Costs" in section 6).

Basic Design D is a three-layer cover design consisting of a vertical percolation layer, lateral drainage layer, and barrier layer.

The HELP Model provides for modeling a waste layer. However, a waste layer was not used in the model runs for this report, since such a layer has little effect on the ultimate amount of leachate produced at the bottom of the landfill, and any such effect was assumed to be a constant value for all cover types used.

Liners (beneath the waste layer) were not included in any of the cover types modeled, since the main focus of this report is on landfill covers. It is assumed that the effectiveness of a liner in reducing leachate can be extrapolated from the performance of an identical lateral drainage layer-barrier layer combination in the cover.

The soil types used in the cover designs, numbered 1 through 21, refer to the default soil types listed in the HELP Model User's Guide (Schroeder et al., 1984a), and are shown in Table 1

TABLE 1. DEFAULT SOIL CHARACTERISTICS

Soil HELP	Texture USDA	Class USCS	MIR* in/hr	Porosity Vol/Vol	Field Capacity Vol/Vol	Wilting Point Vol/Vol	Hydraulic Conductivity in/hr	CON** 0.5mm/day
1	CoS	GS	0.500	0.351	0.174	0.107	11.950	3.3
2	C	GP	0.450	0.376	0.218	0.131	7.090	3.3
3	CoSL	SW	0.400	0.389	0.199	0.066	6.620	3.3
4	S	SM	0.390	0.371	0.172	0.050	5.400	3.3
5	LS	SM	0.380	0.430	0.160	0.060	2.780	3.4
6	LFS	SM	0.340	0.401	0.129	0.075	1.000	3.3
7	LVFS	SM	0.320	0.421	0.176	0.090	0.910	3.4
8	SL	SM	0.300	0.442	0.256	0.133	0.670	3.8
9	FSL	SM	0.250	0.458	0.223	0.092	0.550	4.5
10	VFSL	MH	0.250	0.511	0.301	0.184	0.330	5.0
11	L	ML	0.200	0.521	0.377	0.221	0.210	4.5
12	SIL	ML	0.170	0.535	0.421	0.222	0.110	5.0
13	SCL	SC	0.110	0.453	0.319	0.200	0.084	4.7
14	CL	CL	0.090	0.582	0.452	0.325	0.065	3.9
15	SICL	CL	0.070	0.588	0.504	0.355	0.041	4.2
16	SC	CH	0.060	0.572	0.456	0.378	0.065	3.6
17	SIC	CH	0.020	0.592	0.501	0.378	0.033	3.8
18	C	CH	0.010	0.680	0.607	0.492	0.022	3.5
19	waste	waste	0.230	0.520	0.320	0.190	0.283	3.3
20	barrier	soil	0.002	0.520	0.450	0.360	0.000142	3.1
21	barrier	soil	0.001	0.520	0.480	0.400	0.0000142	3.1

*MIR = Minimum Infiltration Rate
**CON = Evaporation Coefficient

with their characteristics. Soil characteristic data is automatically supplied by the HELP Model if a default soil type is selected by the user. (Users can supply their own soil data if desired.) Referring to Table 1, a description of a soil type can be determined from the column labeled USDA under Soil Texture Class. The abbreviations used in this column are as follows: Co=coarse; S=sand if it appears last or alone in the abbreviation, and sandy if otherwise (unless followed by I); L=loam if it appears last or alone, and loamy if otherwise; F=fine; V=very; SI=silty; and C=clay.

Reference to a cover type in this report will be followed by an abbreviated description of its design. For example, cover type D4a (VP-24-10; LD-24-1-3-50; B-24-20) consists of the following layers: (1) a vertical percolation layer 24 inches thick, composed of soil type 10; (2) a lateral drainage layer 24 inches thick, composed of soil type 1, with a slope of 3 per cent and a drain spacing of 50 feet; and (3) a barrier layer 24 inches thick, composed of soil type 20. The vertical percolation layer is the topmost layer.

For another example, cover type D1e (VP-24-10; LD-24-3-6-100; B-24-20) consists of : a vertical percolation layer 24 inches thick and composed of soil type 10; a lateral drainage layer 24 inches thick, composed of soil type 3, with a slope of 6 per cent and a drain spacing of 100 feet; and a barrier layer 24 inches thick and composed of soil type 20.

The various cover types were tested using climatic data for ten cities, representing a wide range of climatic conditions. A list of the cities, with additional information about related parameters used with each city, is shown in Table 2.

Vegetation type and evapotranspiration depth for the surface vertical percolation layer are two input parameters that are required for the HELP Model. Vegetation type can be either grass or row crops. The vegetation types and ET depths assumed for each city for many of the HELP Model runs made for this report are shown in Table 2. The type of vegetation chosen for each city was based on an estimate of an untended stand of vegetation under local climatic conditions. These types are referred to as "local grass" or "local row crops". The vegetation type used for runs of a given cover design is shown in Appendix A in the VEGETATION column. ET depths were based on values given in the HELP Model documentation.

Table 3 shows the average annual precipitation for the 10 cities (data provided by the HELP Model), and the number of years of record on which the precipitation data is based.

Temperature and solar radiation data was not available for all ten cities, so in some cases temperature data from a nearby city were used. The cities used for temperature and solar radiation data, and the mean monthly temperature for January and July for these cities, are shown in Table 3.

Slope and roughness of the surface layer are not considered directly by the HELP Model in computing the runoff component of the water balance. Computation of runoff is based in part on a runoff curve number. Default runoff curve number values are provided by the HELP Model for a given vegetation type and

TABLE 2. CITIES USED IN HELP MODEL RUNS

City	Code	Grass	ET Depth	Row Crops	ET Depth
Denver, CO	DCO	poor	7"	fair	10"
San Francisco, CA	SFCA	fair	10"	fair	10"
Corpus Christi, TX	CCTX	fair	10"	fair	10"
Milwaukee, WI	MWC	good	14"	good	14"
Seattle, WA	SWA	good	14"	good	14"
Newark, NJ	NNJ	good	14"	good	14"
Lexington, KY	LKY	good	14"	good	14"
Houston, TX	HTX	excellent	18"	good	14"
Columbia, SC	CSC	excellent	18"	good	14"
New Orleans, LA	NOLA	excellent	18"	good	14"
Cover Types A1,A2		bare dirt	4"		

TABLE 3. CLIMATIC DATA FOR CITIES USED IN HELP MODEL RUNS

City	Annual Precip. (inches)	Years Data On Record	Location of Temperature Station	Mean Monthly Temp. (F) Jan	July
Denver, CO	14.93	20	Denver	28.90	71.35
San Francisco, CA	19.73	20	Santa Maria	51.40	62.30
Corpus Cristi, TX	30.50	20	San Antonio	51.69	85.94
Milwaukee, WI	33.07	11	Madison	18.51	71.39
Seattle, WA	34.98	20	Seattle	40.13	64.87
Newark, NJ	40.66	20	New York	32.40	76.63
Lexington, KY	42.11	10	Lexington	32.87	77.41
Houston, TX	49.48	11	San Antonio	51.69	85.94
Columbia, SC	51.69	20	Watkinsville, GA	43.43	79.90
New Orleans, LA	56.69	20	New Orleans	53.30	83.37

default soil type. The default runoff curve number values for selected default soil and vegetation types are shown in Table 4. Manual values for the runoff curve number can be entered by the user to allow for different values of surface slope and roughness. Additional information on runoff curve numbers is given in section 3 of this report. For more information on the procedure used by the HELP Model to compute runoff (and other water balance components), see Schroeder et al., 1985b.

TABLE 4. DEFAULT RUNOFF CURVE NUMBERS PROVIDED BY THE HELP MODEL

Soil Type	Vegetation						
	Bare Ground	Poor Grass	Fair Grass	Good Grass	Exc. Grass	Fair Row Crops	Good Row Crops
5	80.96	74.13	66.65	67.56	38.18	76.26	48.33
10	88.12	82.22	76.21	77.42	57.7	84.32	65.87
15	95.25	90.13	86.75	87.26	76.65	91.68	81.43

SECTION 5

PERFORMANCE OF COVER DESIGNS

CRITERIA FOR EVALUATING DESIGN PERFORMANCE

Each layer in a cover design has several design parameters which affect the performance of the cover. The evaluation process consisted of testing the effect of these parameters on the outputs (particularly cover percolation) of a given cover design. These parameters are: vegetation type, evapotranspiration depth, and runoff curve number for VP layers; slope and drain spacing for LD layers; and thickness and soil type for VP, LD and barrier layers. Selected parameters were tested for single layer (Type B) and double layer (Type A and C) design types. All parameters were tested for three layer (Type D) designs.

One method used to evaluate cover designs was to graph, for the ten cities, the annual water budgets of two or more cover designs which differ in one parameter (see Figures 21 and 22.) The graphs can be compared to show how all the outputs of a given design, under different climatic conditions, are affected by varying a given parameter.

Another method used was to graph for the ten cities a single output (such as cover percolation) for two or more designs which differ by a single parameter. For example, Figure 24 compares cover percolation for Types D1a, D1b, and D1f, which differ only in the soil type of the VP layer.

The means of testing many of the parameters for the three-layer covers consisted of comparing the performance (i.e., cover percolation) of a "control" design at the ten cities with the performance of an equivalent design which differed from the control only in the parameter being tested. The control used in many of the tests was a D1b cover design (VP-24-10; LD-24-3-3-50; B-24-20). For example, Figure 28 compares cover percolation for Type D1b and Type D2 (VP-24-10; LD-12-3-3-50; B-24-20).

Linear regression equations of cover percolation versus precipitation for the ten cities were developed and plotted for some of the cover types. These plots give a general indication of how much of the difference in cover percolation between cities is explained by variations in precipitation alone. For example, see Figure 5.

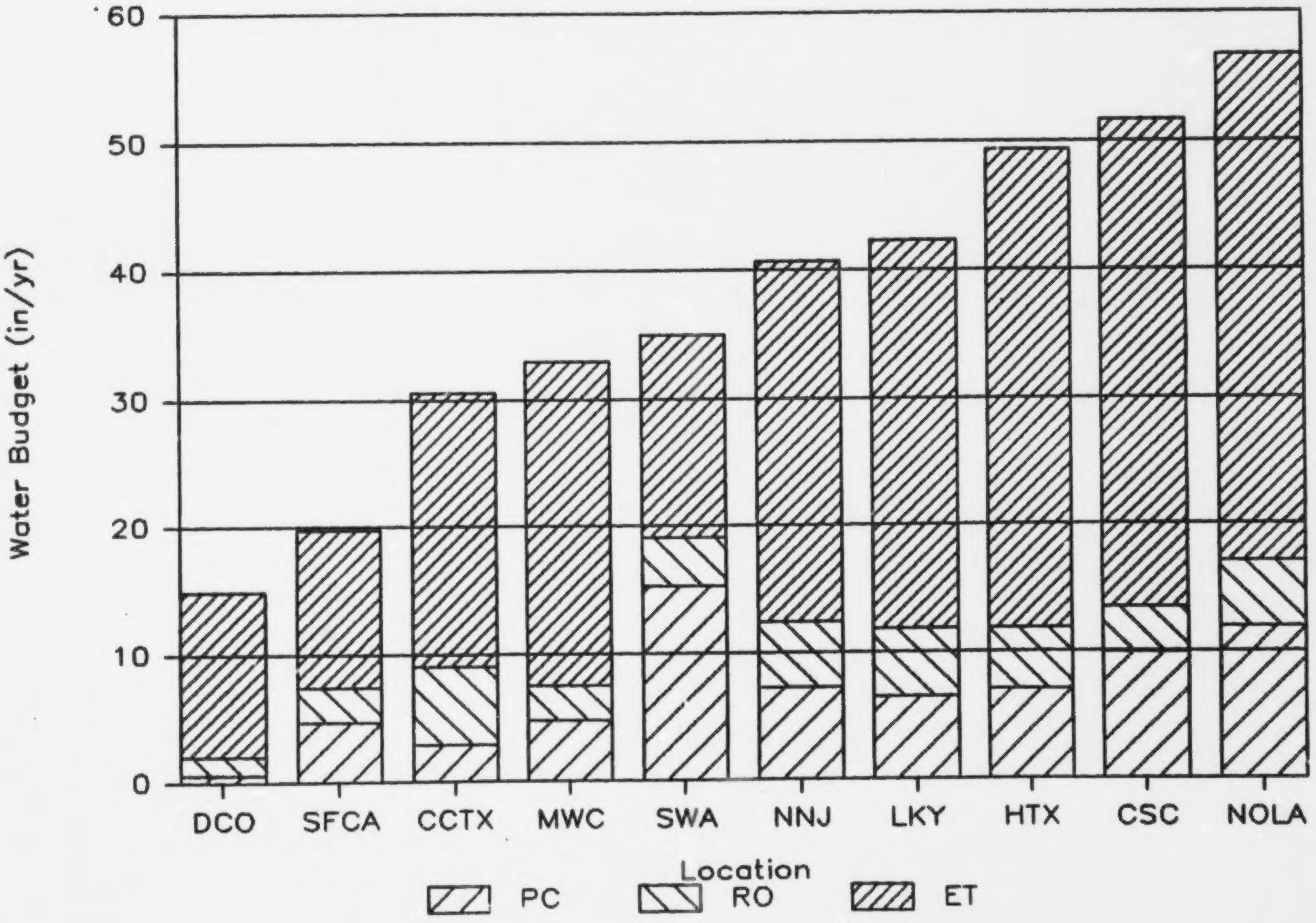
A summary table of the results for all the HELP Model runs performed for this study, showing precipitation, runoff, evapotranspiration, cover percolation, lateral drainage, maximum daily head, and maximum saturation (thickness above the barrier layer) for each cover type tested, is given in Appendix B.

ONE LAYER COVER DESIGNS (TYPE B)

Soil type and vegetation type were the only parameters evaluated for the one layer designs. The designs tested were B1a (VP-24-5), B1b (VP-24-10) and B1c (VP-24-15), which use three different soil types, ranging from a loamy sand (soil type 5) to a very fine sandy loam (soil type 10) to a silty clay loam (soil type 15). The water balance for cover type B1c for the 10 cities is shown in Figure 3, where PC represents average annual cover

FIGURE 3

Cover Type B1c



percolation, RO is average annual runoff, and ET is average annual evapotranspiration. The labels along the horizontal axis represent the cities in Table 2. The total height of each bar represents the average annual precipitation for the given city.

Cover percolation for types B1a, B1b, and B1c at the ten cities is shown in Figure 4. Average annual cover percolation is greater than 3 inches for these types at the locations tested, with the exception of cover B1c in Denver.

Evapotranspiration for these cover types increases as the soil used varies from a sandy soil (in type B1a) to a clay soil (in type B1c). This is due to an increase in plant available water (the difference between soil water content at field capacity and soil water content at the wilting point). Runoff also increases as the soil varies from sand to clay, since the infiltration rate of clay soils is less than for sandy soils.

Figure 5 shows the graph of a linear regression of cover percolation versus precipitation for cover Type B1c. The variation in percolation is fairly well accounted for by precipitation, except for Seattle, which lies well off the regression line. This is because the evapotranspiration for Seattle is proportionately less than for most of the other cities tested.

The impact of vegetation type and ET depth on performance of one-layer covers was tested by comparing the runoff, (Figure 6), evapotranspiration (Figure 7), and cover percolation (Figure 8) in the ten cities for a B1c cover using "excellent grass" and an

FIGURE 4

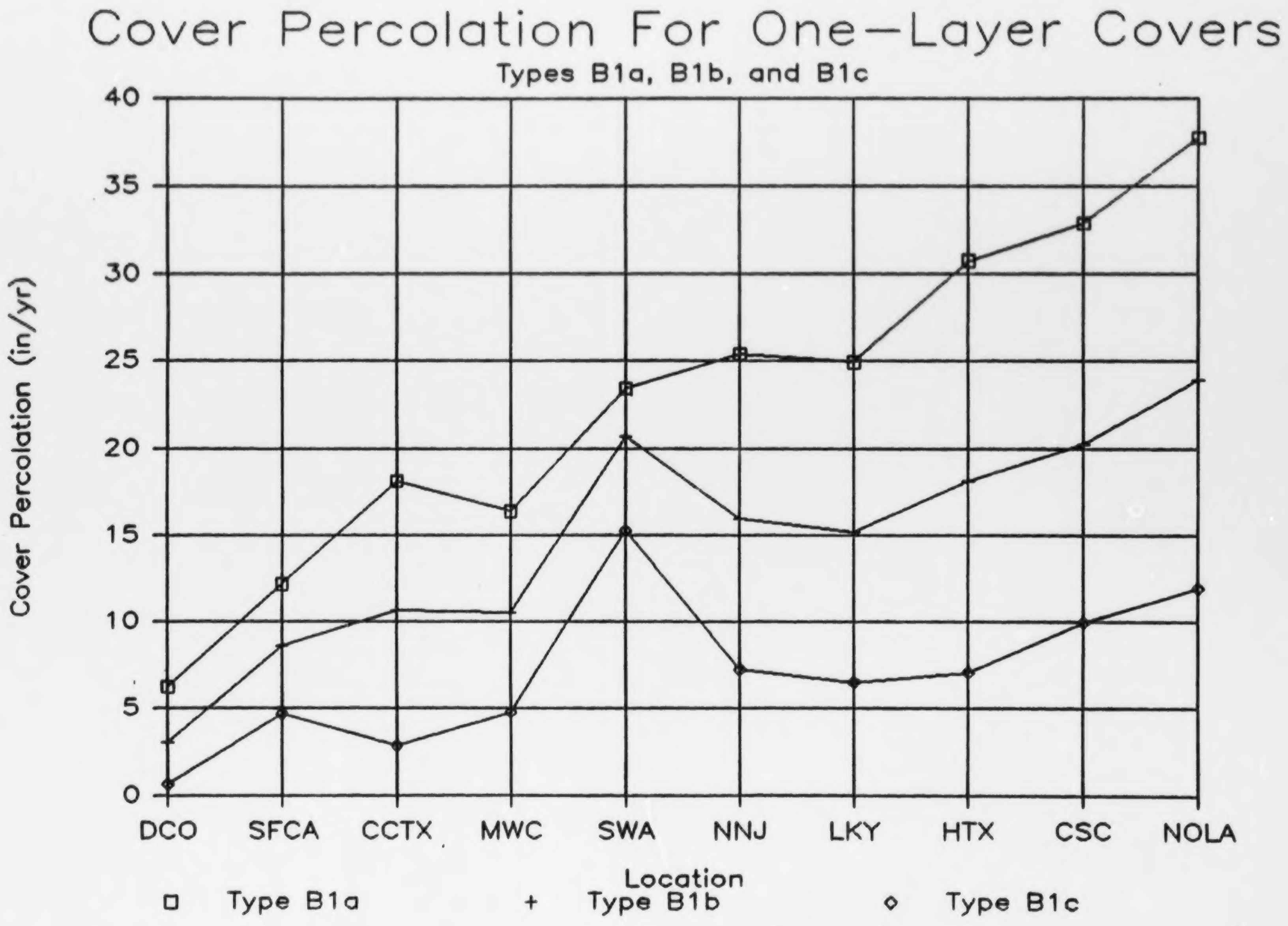

Cover Percolation For One-Layer Covers
Types B1a, B1b, and B1c
Cover Percolation (in/yr)
40
35
30
25
20
15
10
5
0
DCO
SFCA
CCTX
MWC
SWA
NNJ
LKY
HTX
CSC
NOLA
Location
□ Type B1a
+ Type B1b
◇ Type B1c

FIGURE 5

Precipitation vs. Cover Percolation

Type B1c

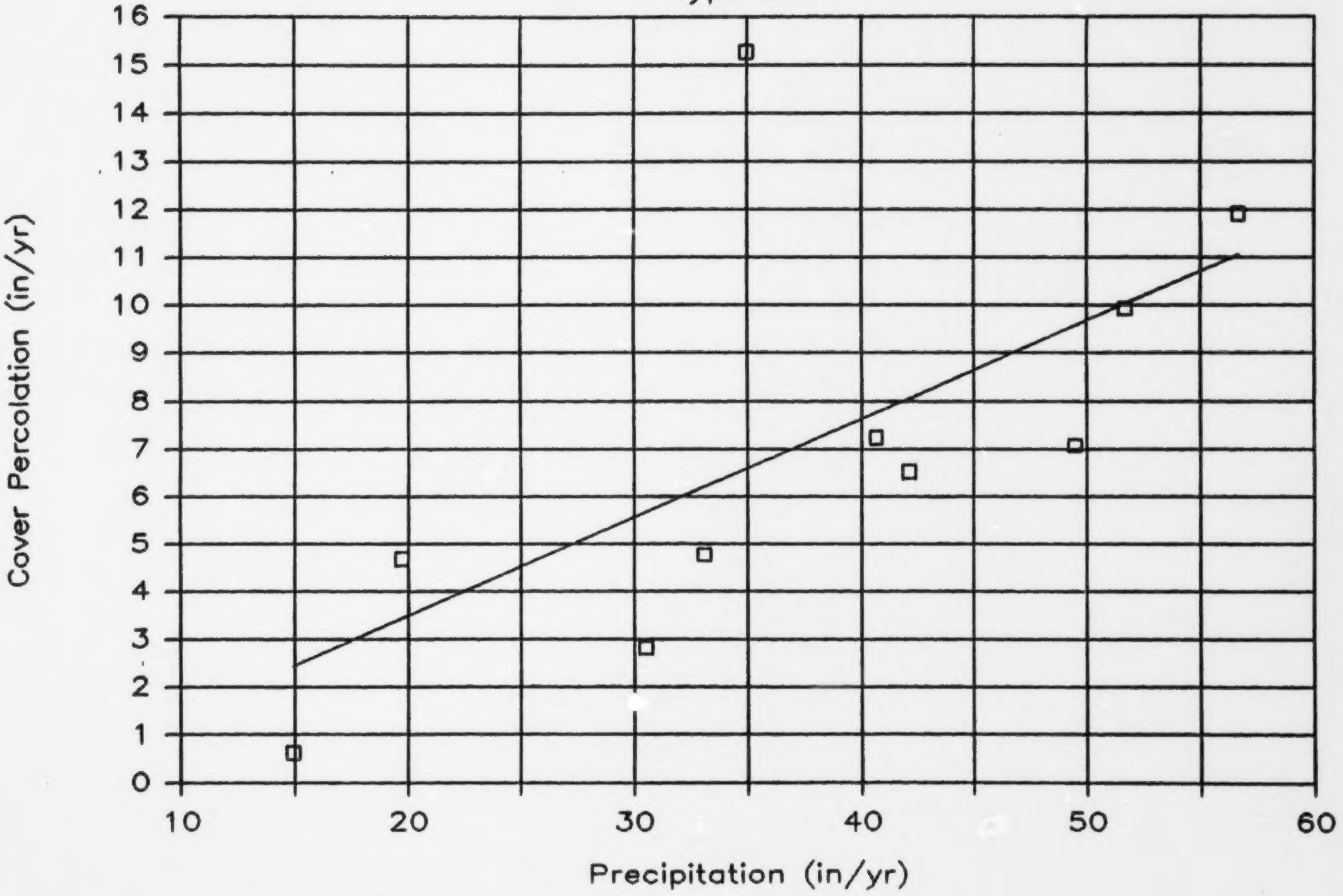
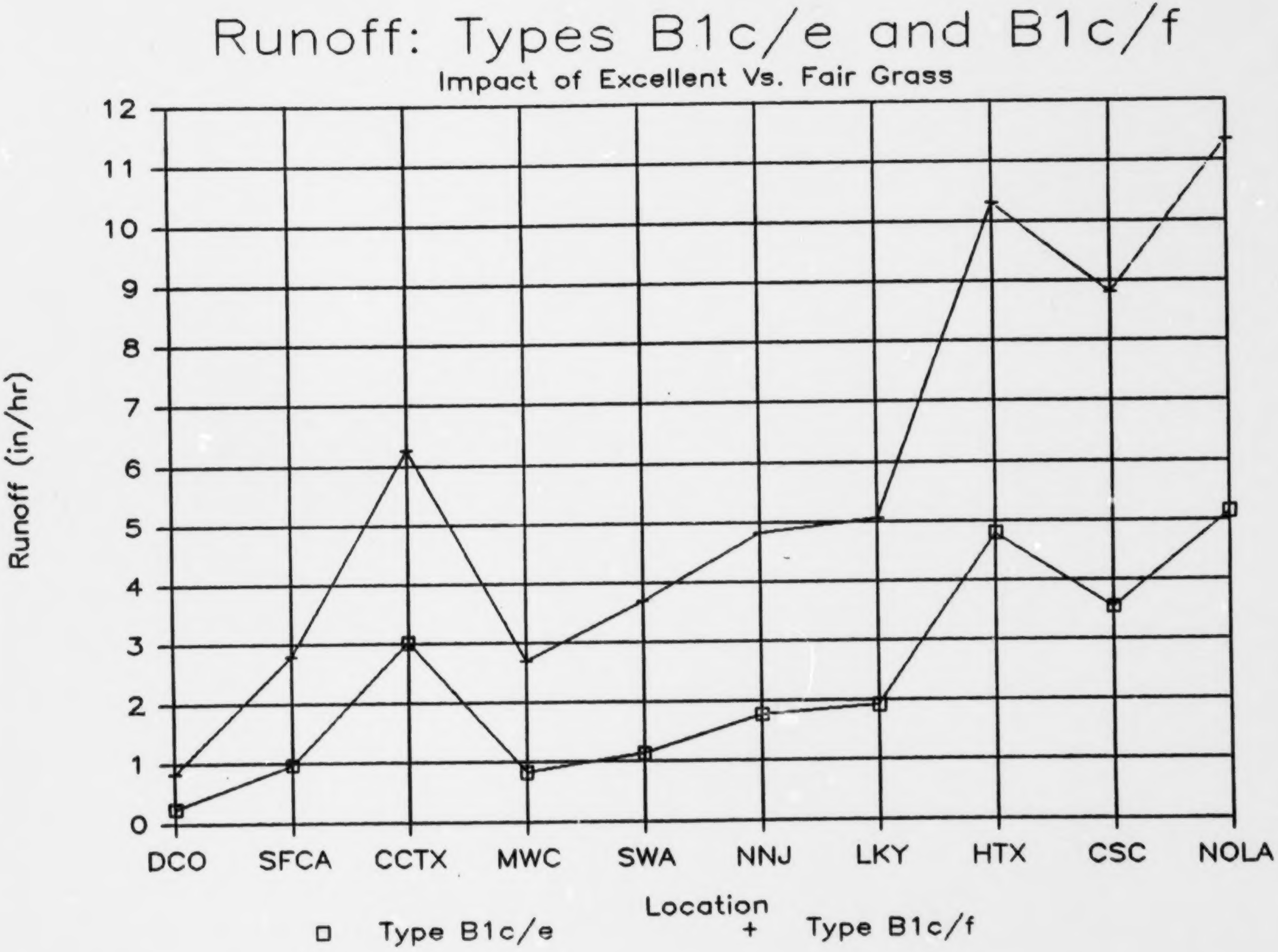


FIGURE 6


Runoff: Types B1c/e and B1c/f

Impact of Excellent Vs. Fair Grass

FIGURE 7

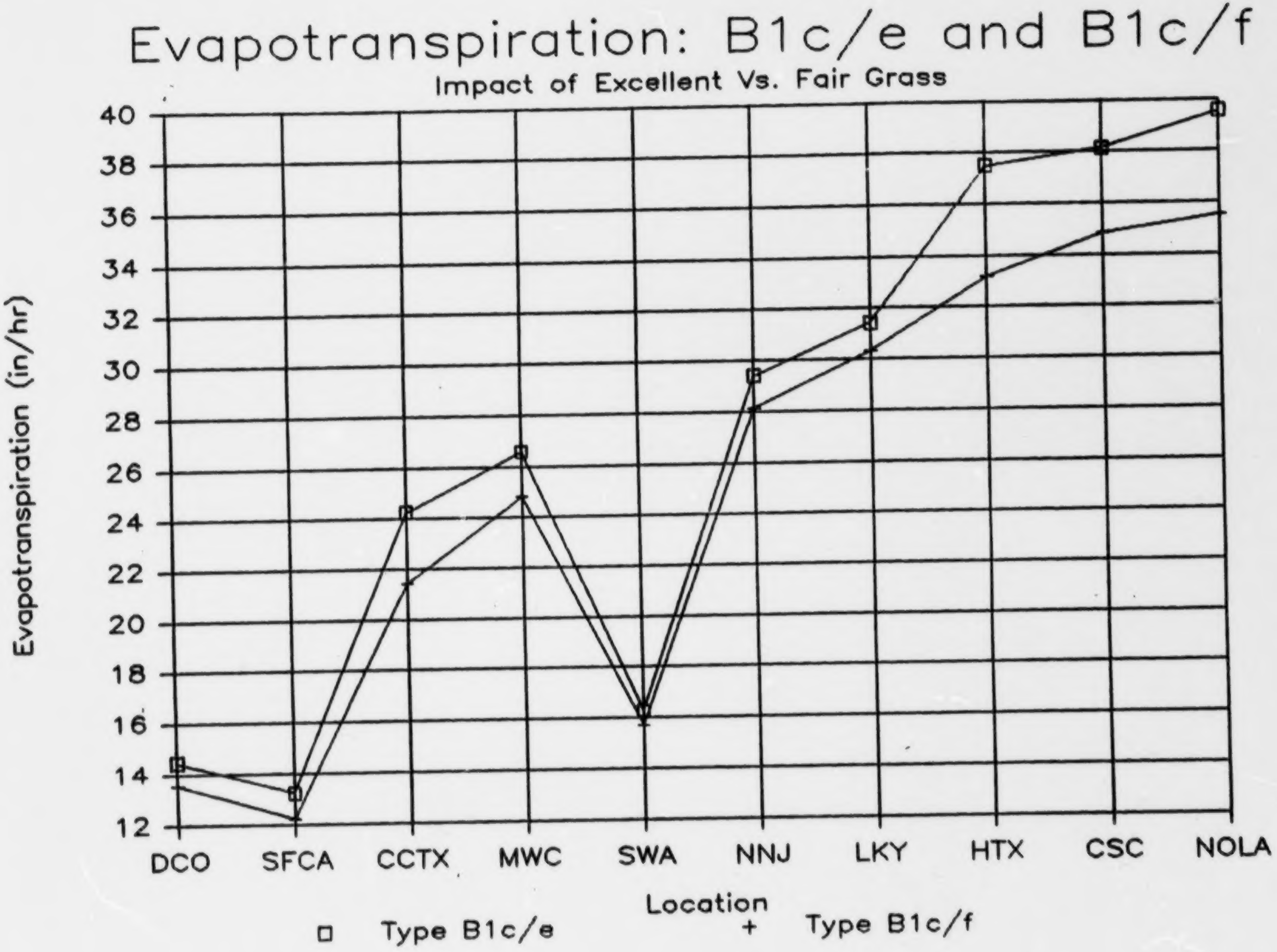
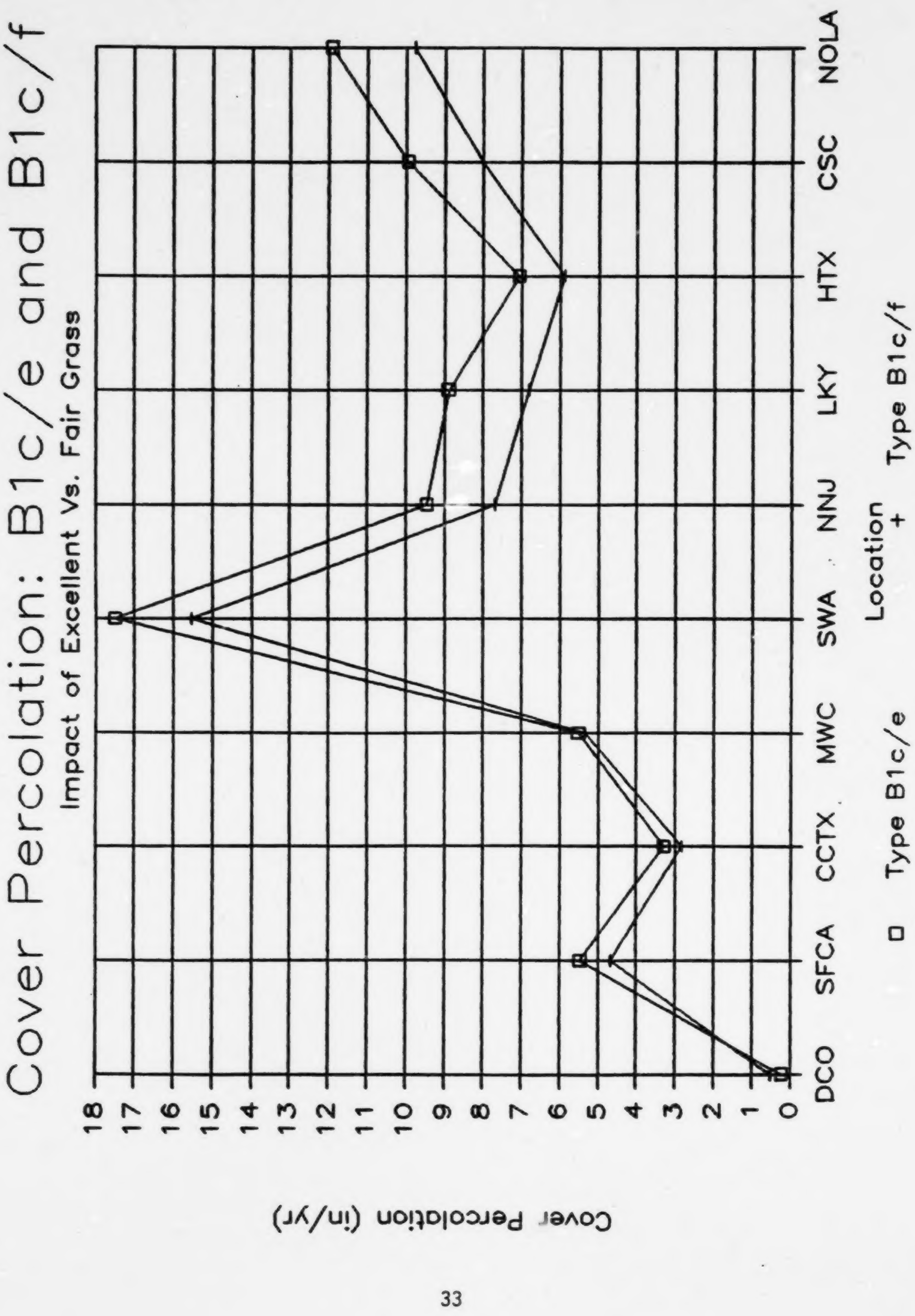

Evapotranspiration: B1c/e and B1c/f
Impact of Excellent Vs. Fair Grass
Evapotranspiration (in/hr)
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
DCO
SFCA
CCTX
MWC
SWA
NNJ
LKY
HTX
CSC
NOLA
Location
□ Type B1c/e
+ Type B1c/f

FIGURE 8


Cover Percolation: B1c/e and B1c/f
Impact of Excellent Vs. Fair Grass
Cover Percolation (in/yr)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
DCO
SFCA
CCTX
MWC
SWA
NNJ
LKY
HTX
CSC
NOLA
Location
□ Type B1c/e
+ Type B1c/f

ET depth of 18 inches, with the outputs of a B1c cover using "fair grass" and an ET depth of 10 inches. The impact of vegetation and ET depth on cover percolation of one-layer covers is determined by their impact on the two other outputs in the water balance, evapotranspiration and runoff.

Runoff in the HELP Model is determined in part by a runoff curve number. Runoff curve numbers are based on a method developed by the Soil Conservation Service, and generally ranges between 15 and 100. A higher value (for a given soil type) indicates that more runoff will be produced. Generally, the runoff curve number will decrease as the density of the vegetation increases, if all other parameters are held constant. The HELP Model supplies a default value for the runoff curve number (RCN) for a given cover design, based on the vegetation and soil type of the surface layer. Table 4 shows the default runoff curve numbers supplied by the HELP Model for soil types 5, 10, and 15, for the range of vegetation types specified in the Model. Note that the default values of the RCN for good grass shown in Table 4 are consistently higher than those for fair grass. This apparent discrepancy was brought to the attention of the authors of the HELP Model.

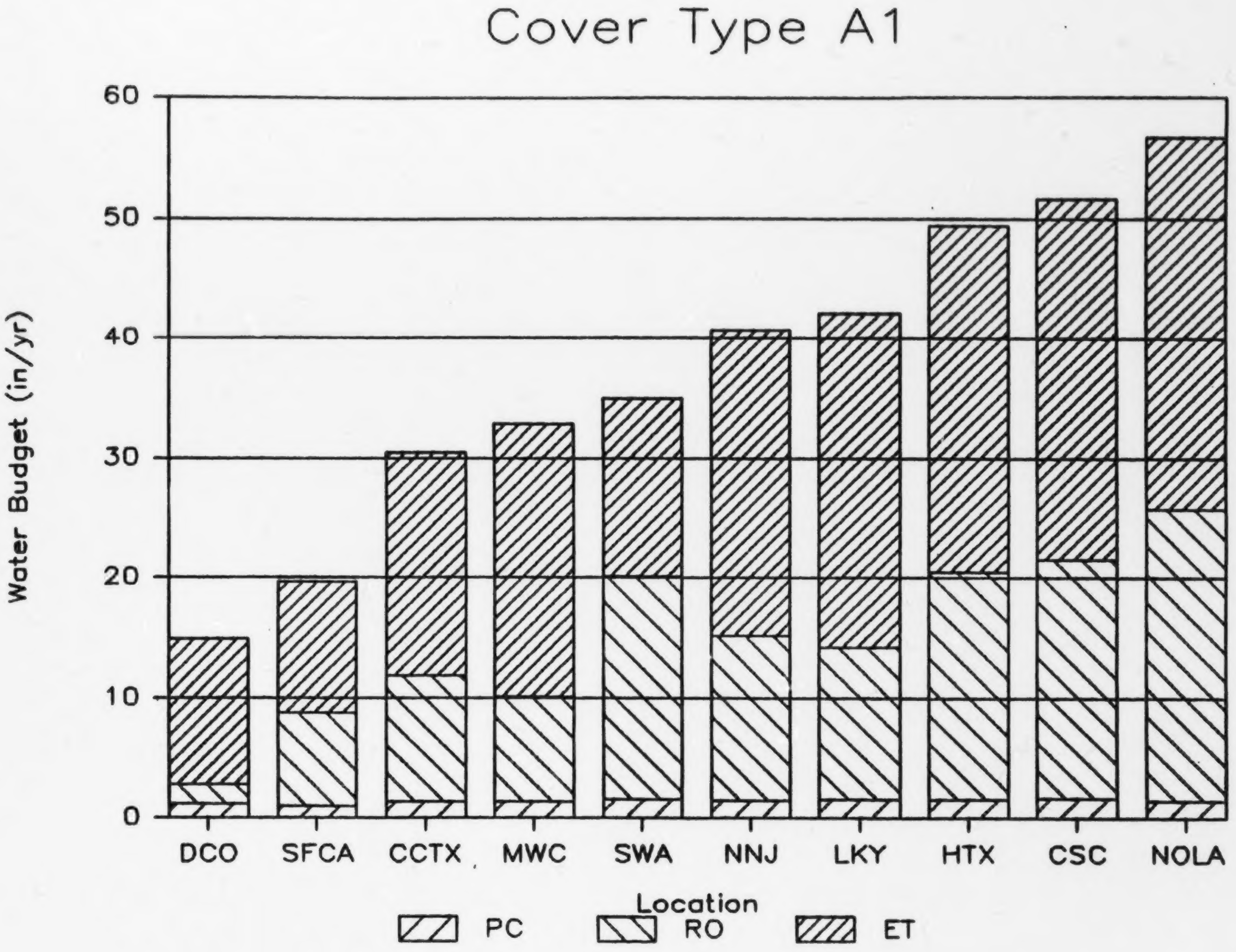
Changes in evapotranspiration and runoff will offset one another when one compares the impact of changing the vegetation type on cover percolation. For example, fair grass results in less evapotranspiration than excellent grass for a given climate and soil type (see Figure 7). However, the default value for the runoff curve number assigned by the HELP Model is significantly greater for fair grass than for excellent grass, for a given soil type (see Table 4). This means that the amount of runoff produced with fair grass is greater than the amount produced with excellent grass (see Figure 6). The net effect of changing the vegetation type on cover percolation depends on whether or not the resulting decrease in evapotranspiration is greater than the increase in runoff. This is determined by several factors, including the soil type of the VP layer, the vegetation types being compared, and precipitation and radiation at the site. For Type B1c, at all of the ten cities except Denver, the increase in runoff resulting from changing the type of grass from excellent to fair, is greater than the resulting decrease in evapotranspiration. Therefore, changing from excellent grass to fair grass results in a net decrease in cover percolation (Figure 8).

TWO LAYER COVER DESIGNS (TYPES A AND C)

Shallow Gravel Layer Over Barrier (Type A)

The only parameter evaluated for this design was thickness of the VP layer. Figure 9 shows the water budget for cover type A1 (VP-6-1; B-12-20) which consists of a shallow, unvegetated gravel layer (6" thick) over a barrier layer. This design results in large amounts of runoff, but has relatively low cover percolation rates for all cities considered. Although the HELP Model shows this design producing large amounts of runoff, in reality much of this runoff would occur as subsurface drainage in the gravel layer. Since coarse gravel is relatively erosion resistant at low slopes and with proper drainage conditions, this

FIGURE 9


Cover Type A1
Water Budget (in/yr)
60
50
40
30
20
10
0
DCO
SFCA
CCTX
MWC
SWA
NNJ
LKY
HTX
CSC
NOLA
Location
PC
RO
ET

cover type is a viable option. However, careful design would be required to control the amount, velocity, and disposition of runoff and subsurface drainage.

Figure 10 shows the effect of the thickness of the surface gravel layer (VP layer) on cover percolation for this cover design. It compares cover percolation for types A1, A2 (VP-4-1; B12-20), and D1b at the 10 test cities. Figure 9 indicates that decreasing the thickness of the gravel layer from 6 inches to 4 inches can reduce cover percolation by as much as 50 percent at some of the dryer cities. This is because saturation of the gravel layer for Type A2 occurs more often, resulting in increased runoff and reduced cover percolation. However, a gravel layer somewhat thicker than 4 inches is probably desirable, since it would be difficult to maintain uniform thickness with a 4 inch layer, especially during construction.

Topsoil over Barrier (Types C1, C2, C3, and C5)

A number of runs were made with a two-layer cover consisting of a vertical percolation layer composed of topsoil, underlain by a barrier layer (Types C1, C2, C3, and C5). Although this design produced fairly low rates of cover percolation in most cases, it also produced high levels of runoff. This implies saturation of the soil profile, with potential flooding of vegetation roots. This is illustrated by Figures 11 and 12, which show the, respectively, the water balances for Types C1b (VP-24-10; B-24-20) and C1c(VP-24-15;B-24-20) in 10 cities. Type C1c would be a viable design in arid climates such as Denver, where both percolation

FIGURE 10

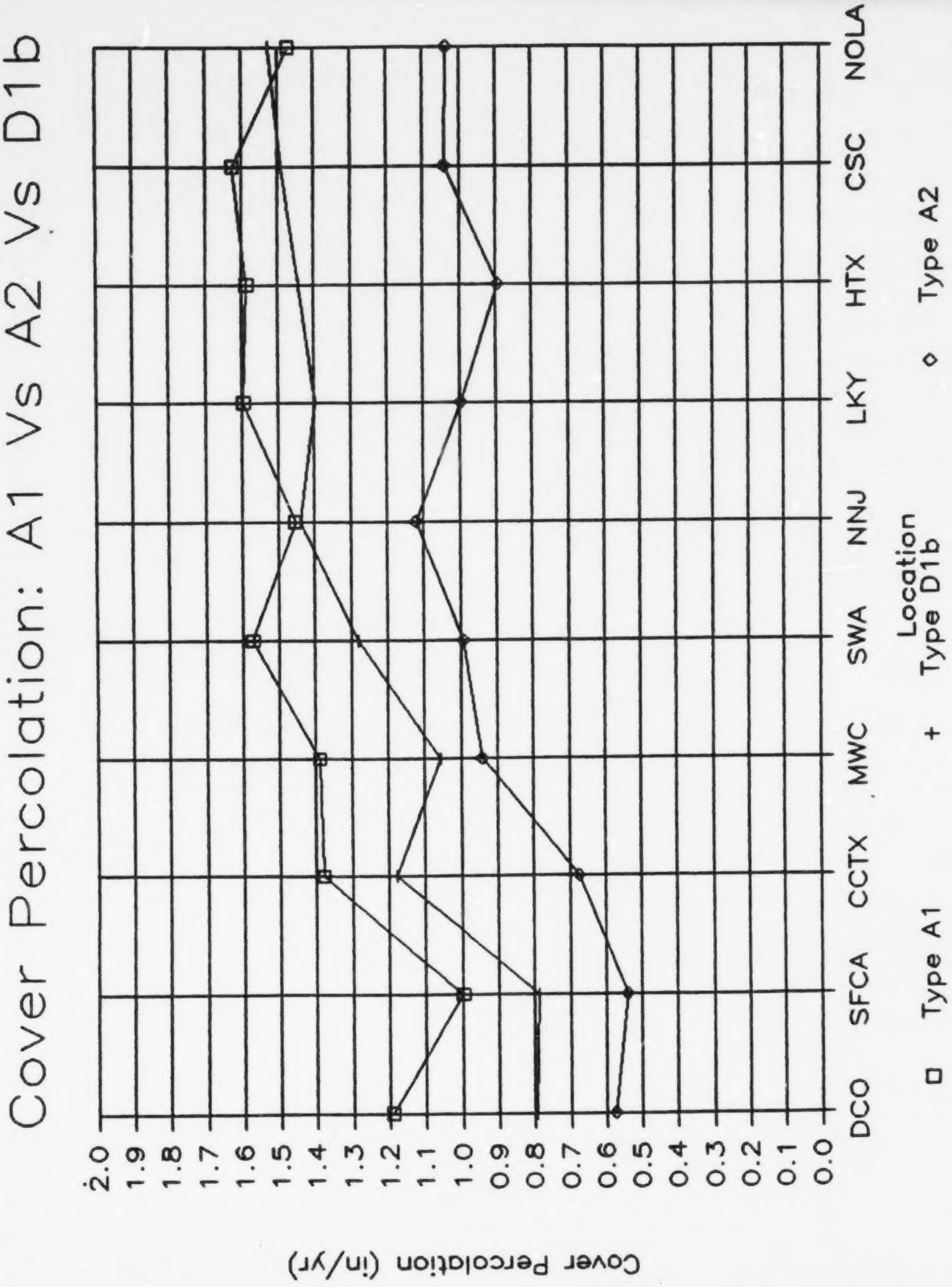
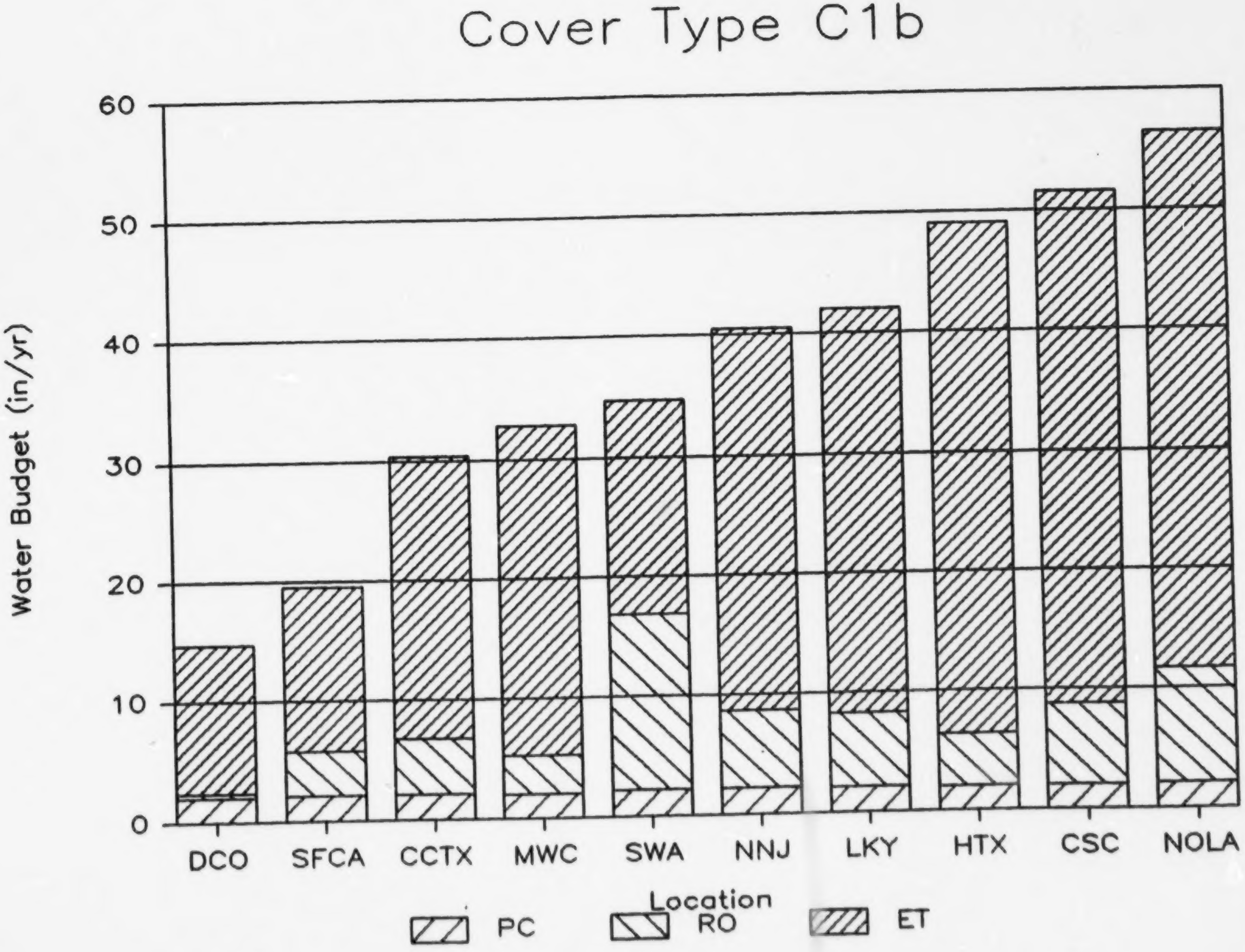

Cover Percolation: A1 Vs A2 Vs D1b
Cover Percolation (in/yr)
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
DCO
SFCA
CCTX
MWC
SWA
NNJ
LKY
HTX
CSC
NOLA
Location
□ Type A1
+ Type D1b
◇ Type A2

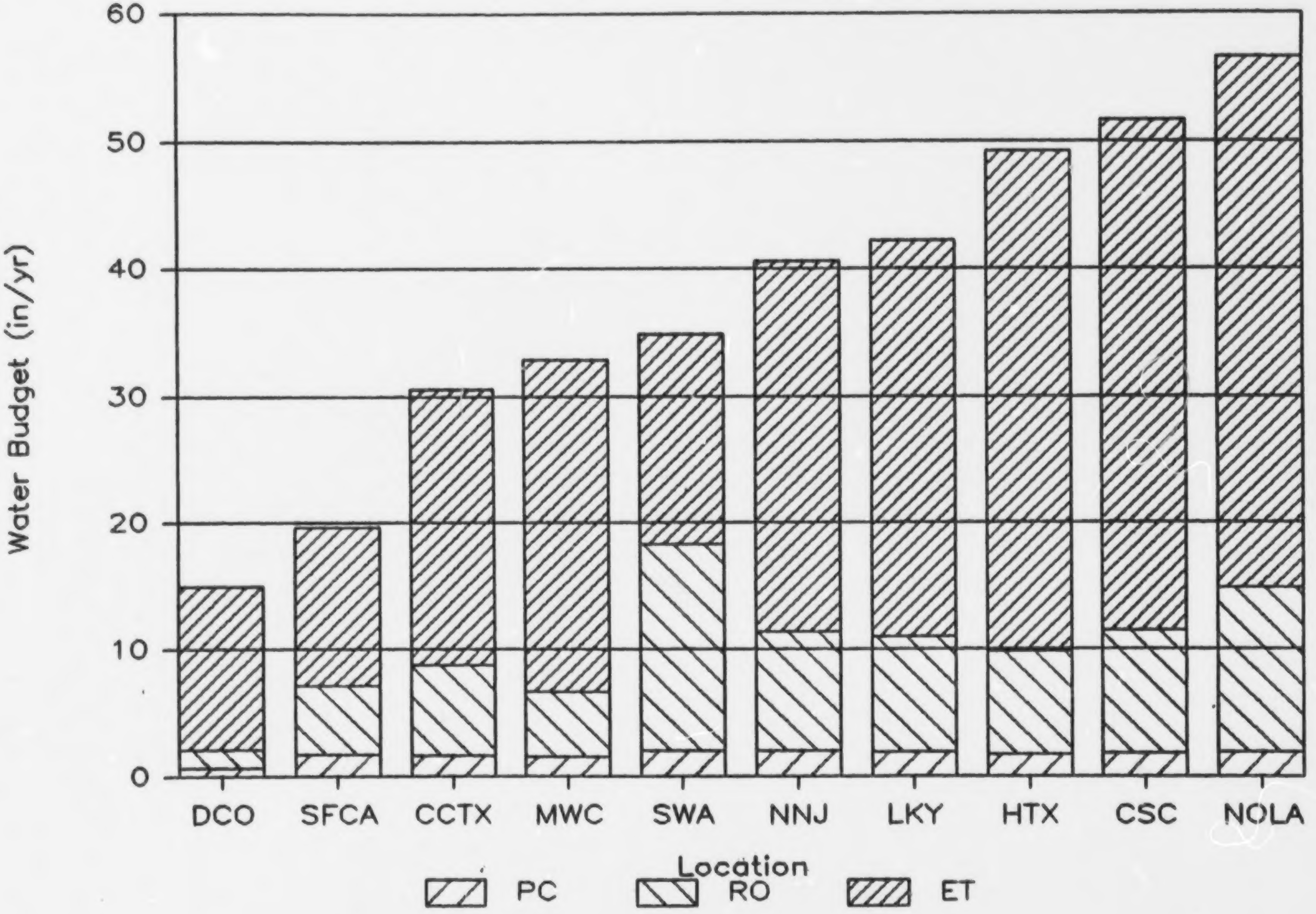
FIGURE 11



Cover Type C1b

FIGURE 12

Cover Type C1c



and runoff are low. However, short duration high intensity rainstorms might still produce excessive runoff with this design. The use of this type in arid climates would require careful design considerations to handle possible excess runoff.

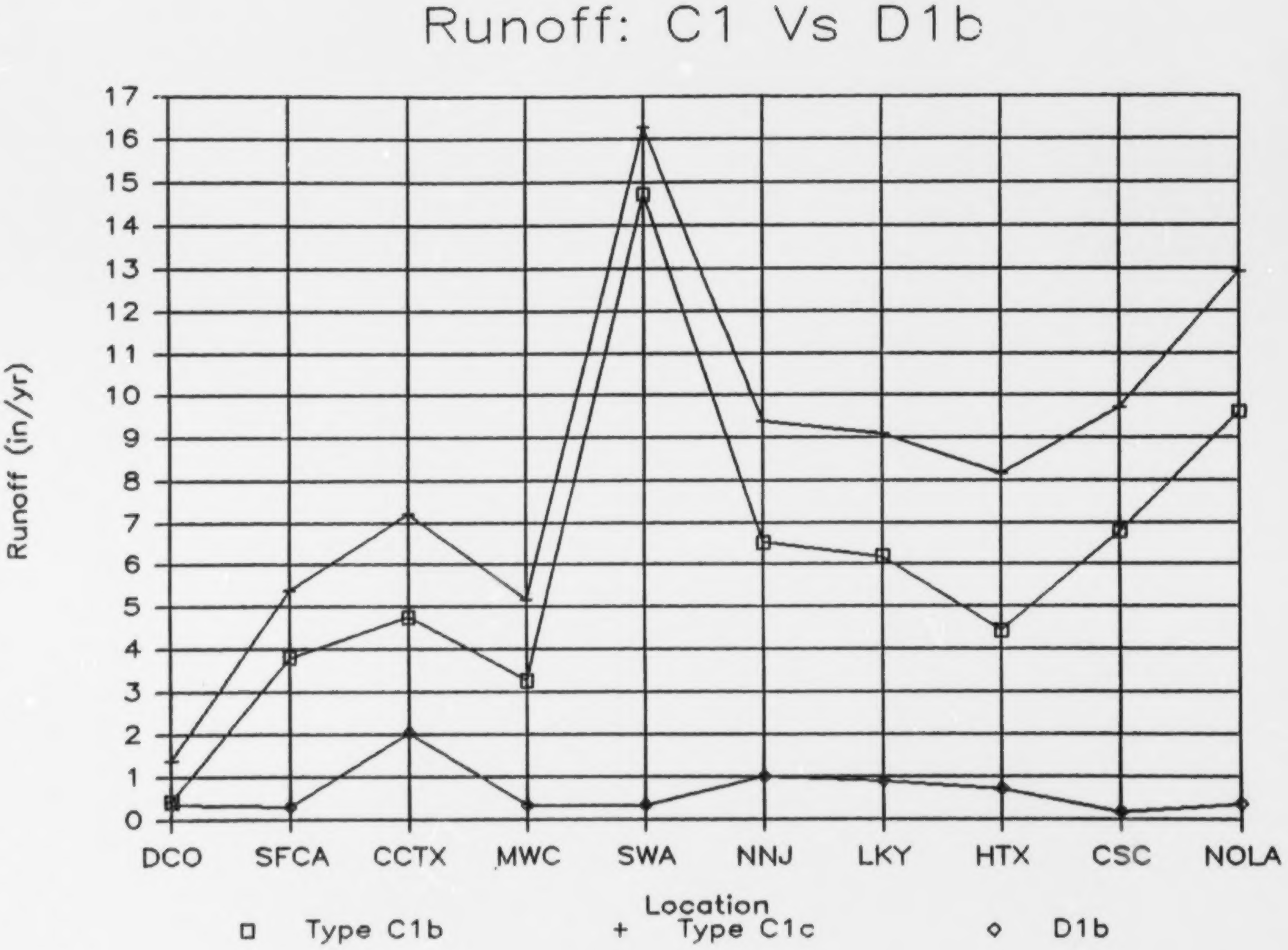
Type C1 was used to evaluate the effect of the soil type of the VP layer on cover percolation for the two-layer cover design. Types C2, C3, and C5 were used to evaluate the effects of thickness of the VP layer, thickness of the barrier layer, and soil type of the barrier layer, respectively. The performance of these types was not analyzed in detail, since the same parameters were analyzed for the three layer cover designs, and the effects were found to be similar for two- and three-layer designs.

The effect of the lack of a drainage layer on runoff production is illustrated in Figure 13 which compares runoff for Types C1b and C1c (two layer designs with no drainage layer) to runoff for Type D1b, which is a three layer design with a drainage layer. The lack of a drainage layer has little effect on runoff production in Denver, a relatively arid climate. However, the effect is dramatic at other locations. Runoff for Type C1b is 10 to 46 times greater than for Type D1b, for cities other than Denver; and 16 to 51 times greater for Type C1c.

Topsoil with Drains Over Barrier (Types C4 and C6)

Cover types C4 and C6 are an attempt to model a continuous top soil layer, with both vertical and lateral drainage, over a barrier layer. (See explanation in Basic Cover Designs section.)

FIGURE 13


Runoff: C1 Vs D1b
Runoff (in/yr)
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
DCO
SFCA
CCTX
MWC
SWA
NNJ
LKY
HTX
CSC
NOLA
Location
□ Type C1b
+ Type C1c
◇ D1b

The soil type and thickness of the VP-LD layer were the two parameters evaluated for this design.

Figure 14 shows the water budget for the ten cities for Type C4a (VP-ET-5; LD-[24-ET]-5-3-50; B-24-20), which uses a sandy soil (soil type 5) in the VP and LD layers. Figure 15 shows the water budget for Type C4e (VP-ET-10; LD-[24-ET]-10-3-50; B-24-20), which uses a loam (soil type 10) in the VP-LD layer. Figure 16 compares cover percolation for Types C4a, C4e and Type D1b (VP-24-10; LD-24-3-3-50; B-24-20), the "control" cover.

The above figures indicate that cover type C4 results in relatively low percolation and runoff for all cities tested, when a sandy soil (such as Soil Type 5) is used in the VP-LD layer. The use of fine-textured soils in the VP-LD layer results in increased percolation and runoff.

Figure 17 shows the effect of thickness of the combined VP-LD layer on cover percolation. This figure compares cover percolation for Types C4a, C6a (VP-ET-5; LD-[36-ET]-5-3-50; B-24-20) and D1b. Type C6a is the same design as C4a, except that it uses a 36 inch topsoil layer instead of 24 inches. The figure indicates that cover percolation is nearly the same for the two types, in cities with less than 50 inches of annual precipitation. In cities with 50 inches or more of annual precipitation, cover percolation is 0.2 to 0.3 inches greater for Type C6a compared to Type C4a. This is because in these cities, the vegetation type is excellent grass, with an ET depth of 18 inches. Therefore, for both Types C4a and C6a, the VP layer is 18 inches. The LD layer is 6 inches for Type C4a and

FIGURE 14

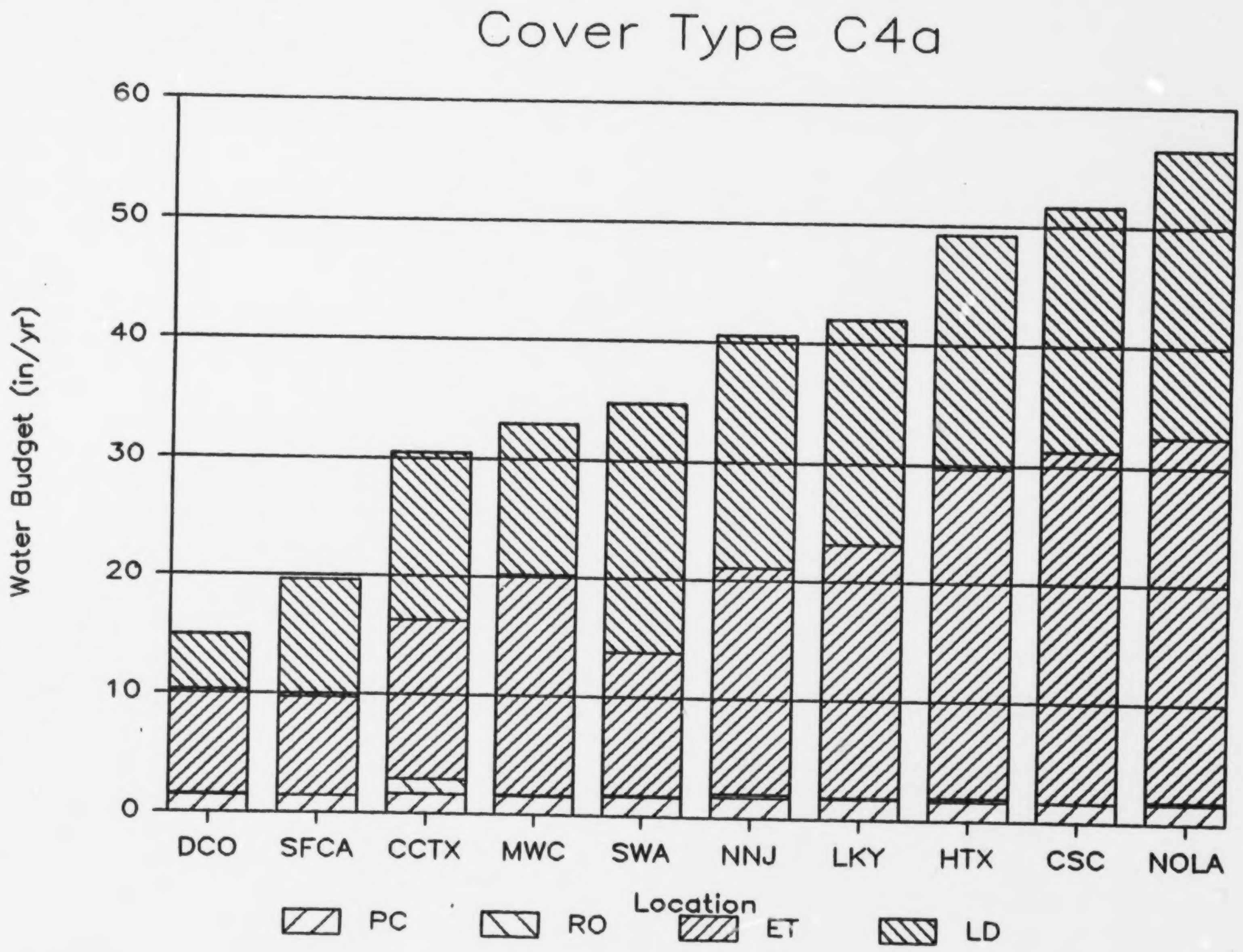

Cover Type C4a
Water Budget (in/yr)
0
10
20
30
40
50
60
DCO
SFCA
CCTX
MWC
SWA
NNJ
LKY
HTX
CSC
NOLA
Location
PC
RO
ET
LD

FIGURE 15

Cover Type C4e

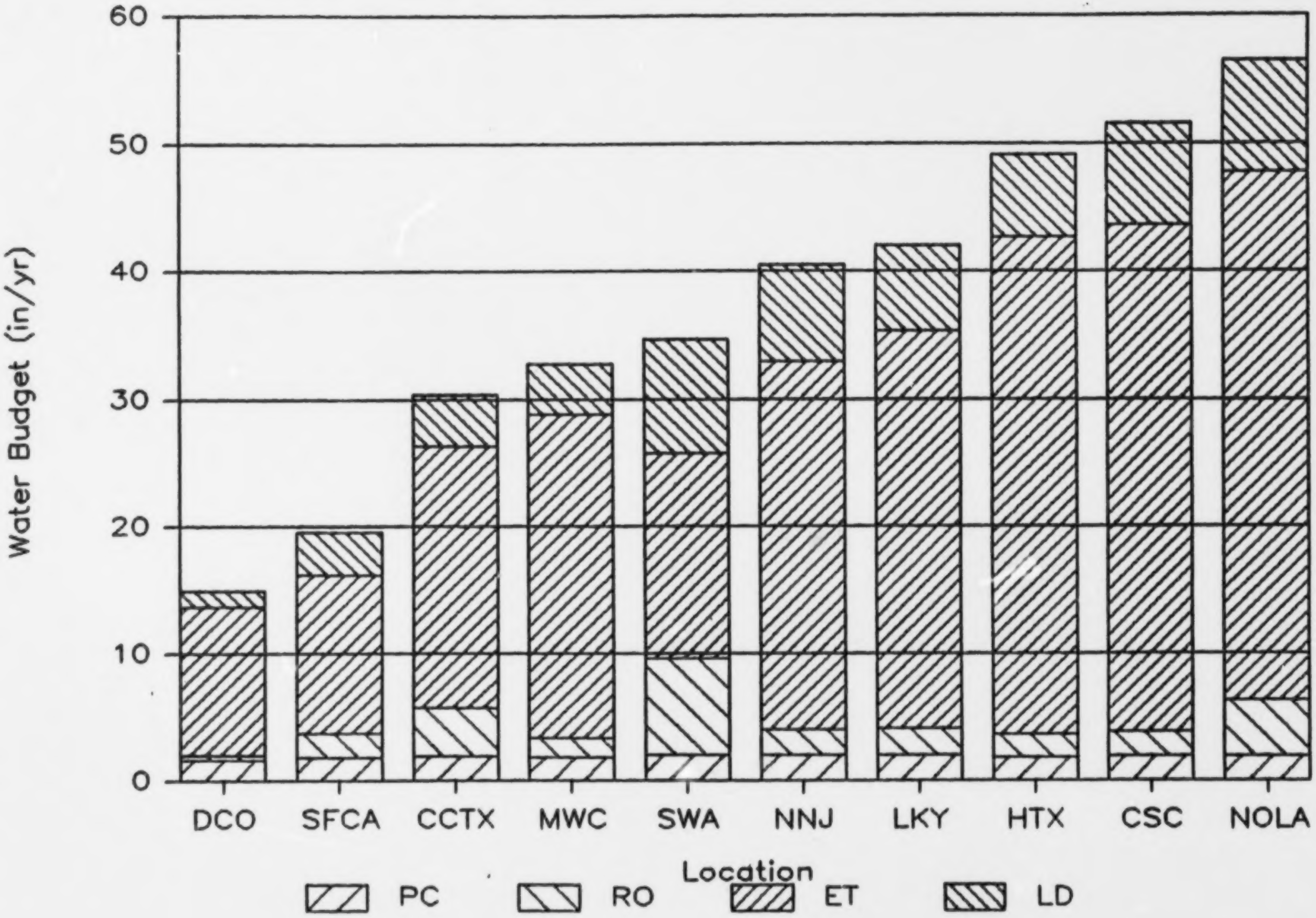


FIGURE 16

Cover Percolation: C4 Vs D1b

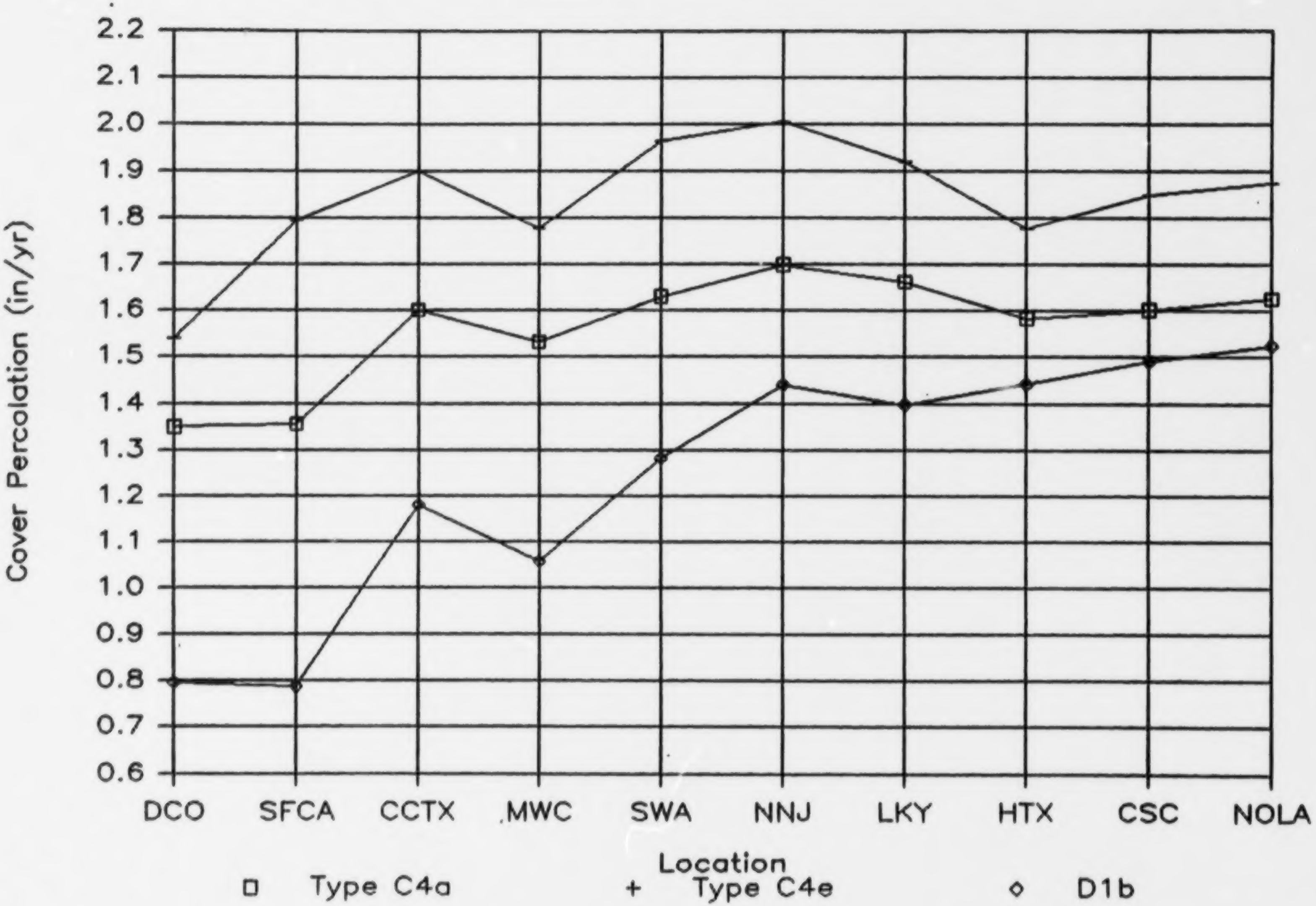
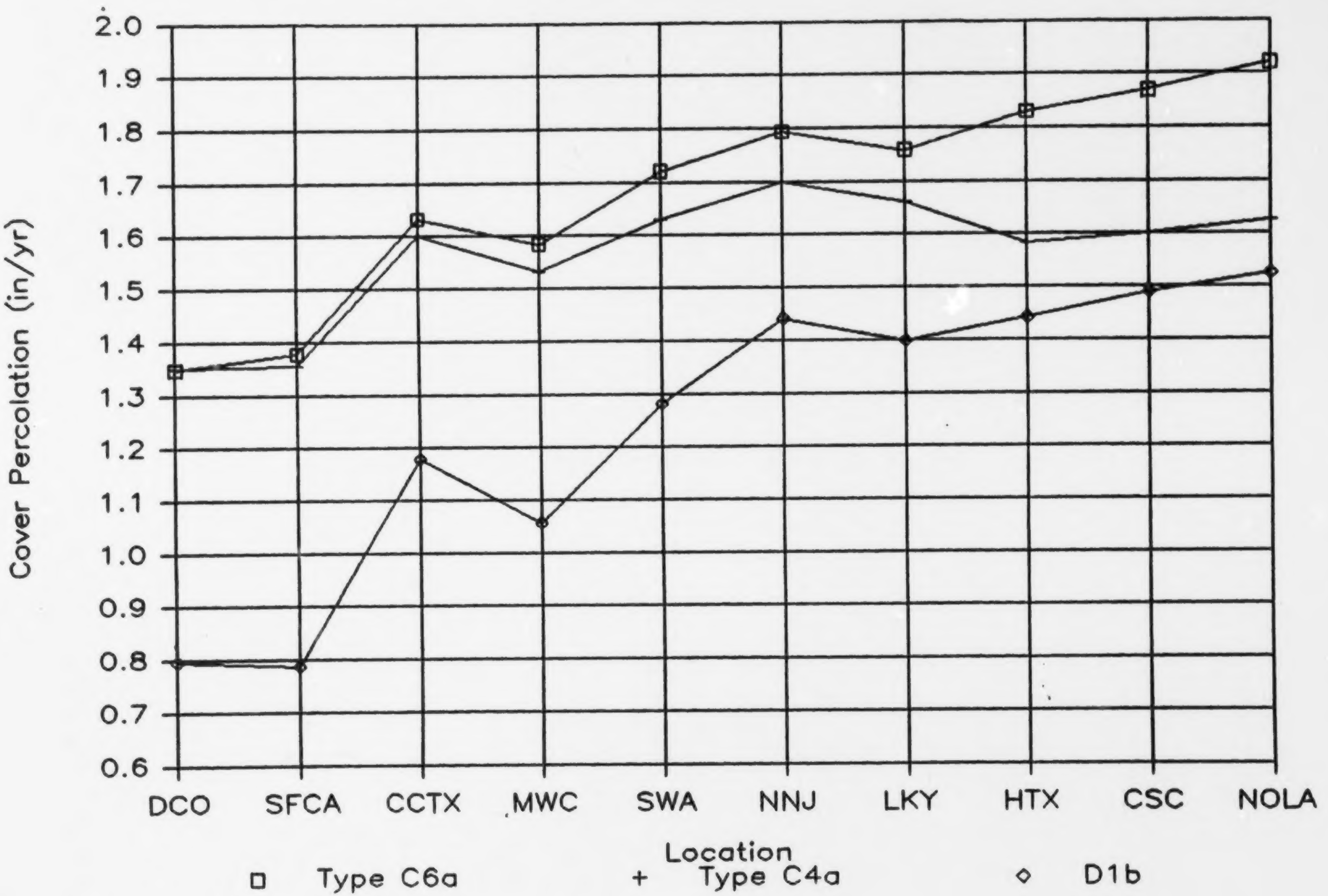


FIGURE 17



Cover Percolation: C6a Vs C4a Vs D1b

18 inches for Type C6a. For Type C4a, a buildup of water over the barrier layer will rapidly saturate the LD layer and move into the VP layer, resulting in greater evapotranspiration and runoff compared to Type C6a. Type C6a will have more lateral drainage than Type C4a under the same climatic conditions. The difference in cover percolation between these two types depends on whether the decrease in evapotranspiration and runoff when changing from Type C4a to C6a is greater or less than the increase in lateral drainage.

THREE LAYER COVER DESIGNS (TYPE D)

Parameters tested for three-layer cover designs include vegetation type, ET depth, thickness, soil type, and runoff curve number of the VP layer; thickness, soil type, slope and drainage spacing of the LD layer; and thickness and soil type of the barrier layer. Cover Type D1b (VP-24-10;LD-24-3-3-50;B-24-20) is a three-layer design that was used as a "control" for comparing the effects of these parameters on the outputs (cover percolation, runoff, lateral drainage and evapotranspiration).

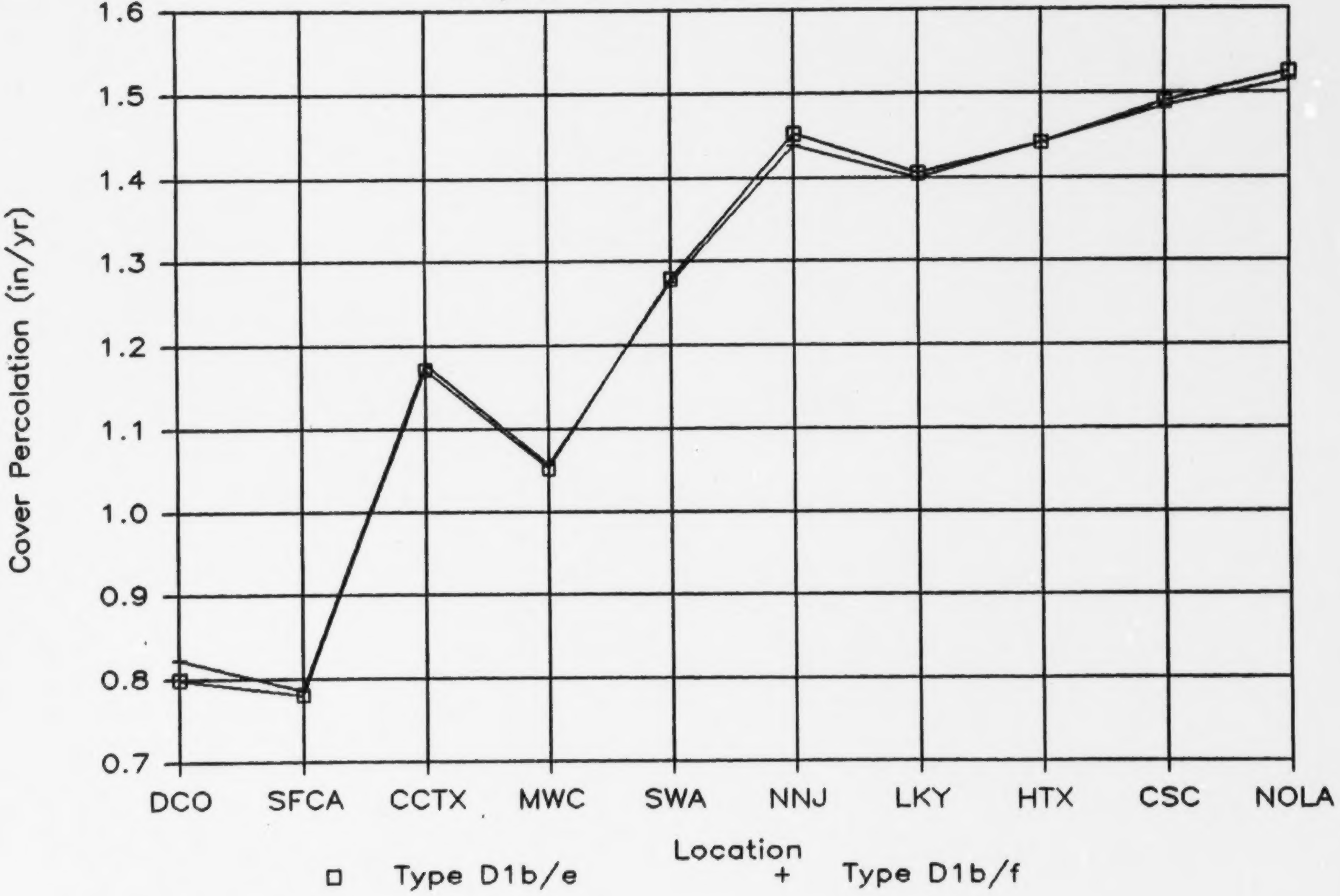
VP Layer

The impact of vegetation type and ET depth was tested by comparing the cover percolation of a D1b cover in the ten cities using "excellent" grass and an ET depth of 18 inches, with the cover percolation of a D1b cover using "fair grass" and an ET depth of 10 inches in all 10 cities. The results, shown in Figure 18, indicate almost no difference in cover percolation for

FIGURE 18

Cover Percolation: D1b/e and D1b/f

Impact of Excellent Vs. Fair Grass



the ten cities tested. As in the case of Type B1c, the impact of grass type and ET depth on cover percolation depends on their impacts on other components of the water balance. Changing the grass type from excellent to fair for Type D1b decreases evapotranspiration and increases runoff, as it does for Type B1c (see Section 3, page 7). However, the magnitude of these changes are different for Type D1b, because these two covers use different soil types in the VP layer. In addition, differences in cover percolation due to vegetation changes in three layer cover designs such as Type D1b, are reduced due to the presence of the lateral drainage layer. The amount of increase or decrease in runoff and evapotranspiration, and the net effect on cover percolation, depends on the VP layer soil type, the vegetation types being compared, the presence of a lateral drainage layer, and the average annual precipitation and solar radiation at the site.

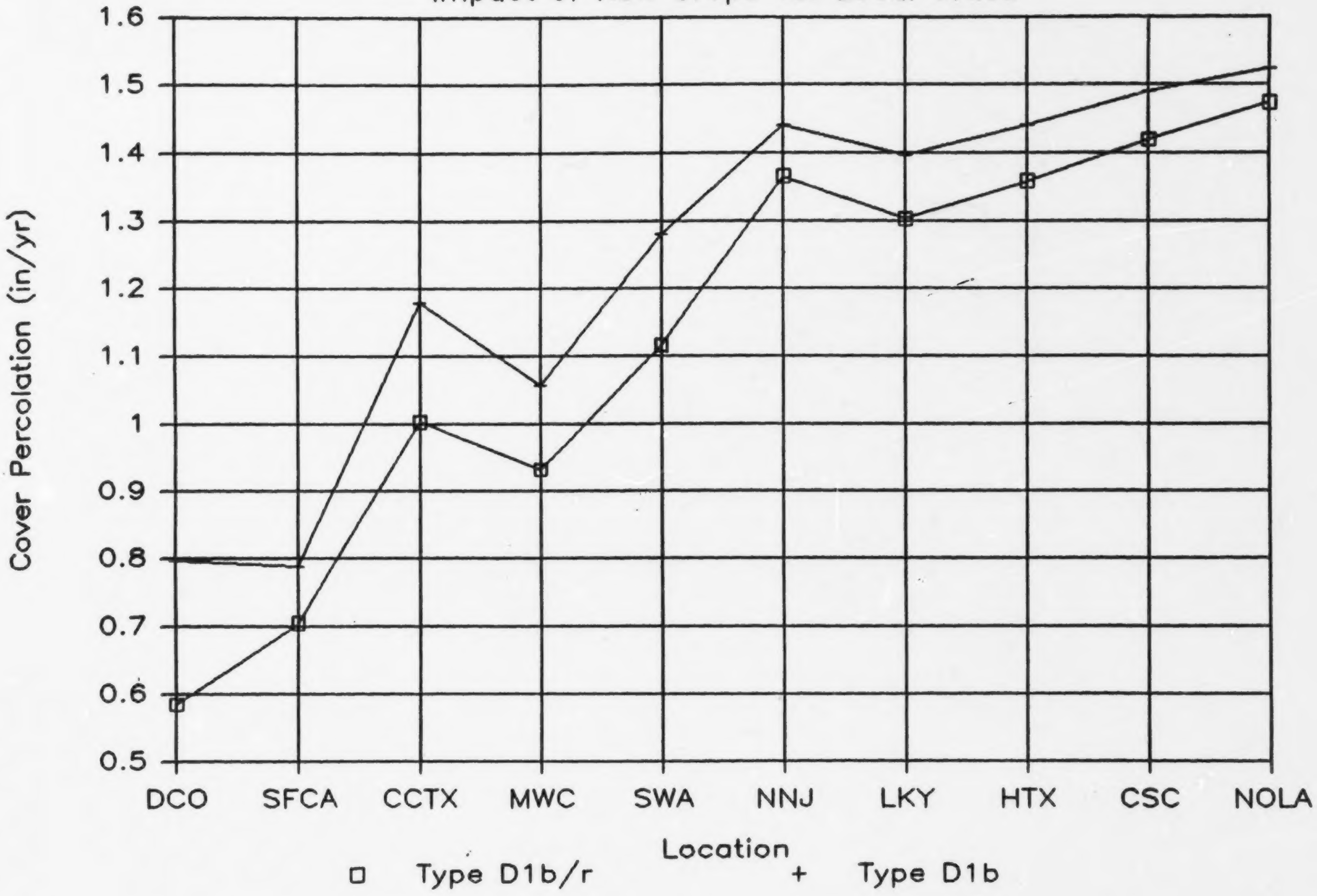
The effect of using the row crop types and ET depths shown in Table 2 was compared to the effect of using the grass types and ET depths shown in Table 2 (referred to as "local grass). The cover percolation for a D1b cover using local row crops types versus a D1b cover using local grass is shown in Figure 19. The use of row crops results in a reduction in cover percolation ranging from three percent for New Orleans to 27 per cent for Denver.

The impact of thickness of the VP layer was evaluated by comparing cover percolation of a D6 cover (same as a D1b, except with a 12-inch VP layer instead of a 24-inch VP layer), with that

FIGURE 19

Cover Percolation: D1b/r and D1b

Impact of Row Crops Vs. Local Grass



of a Dlb. The results, shown in Figure 20, indicate very little difference in cover percolation for these cover types for the ten cities tested.

The impact of different soil types used in the VP layer is illustrated by comparing the water balance for Types Dla (VP-24-5; LD-24-3-3-50; B-24-20), Dlb, and Dlf (VP-24-15; LD-24-3-3-50; B-24-20), which use soil types 5, 10, and 15, respectively, in the VP layer. The water balance for each of these types is shown in Figures 21, 22, and 23. All three of these types produce a relatively low amount of cover percolation. Cover percolation decreases as the soil type ranges from sand to loam and from loam to clay (from soil type 5 to 10 to 15). This is due to the fact that infiltration decreases as soils range from sand to loam to clay, resulting in increased runoff. At the same time, plant available moisture (soil water at field capacity minus soil water at the wilting point) increases, resulting in increased evapotranspiration. Decreased percolation due to increased runoff may be undesirable, since erosion potential is increased; decreased percolation due to increased evapotranspiration is good.

Comparing Types Dlb and Dlf, Dlf has slightly lower cover percolation, more runoff, and less lateral drainage than Type Dlb. Preference for a particular cover would be dependent on site-specific considerations, such as the availability of a particular soil type.

Figure 24 is a comparison of cover percolation for Types Dla, Dlb, and Dlf at the 10 cities used in this study.

Figure 25 is the graph of a linear regression of cover

FIGURE 20

Impact of VP Layer Thickness

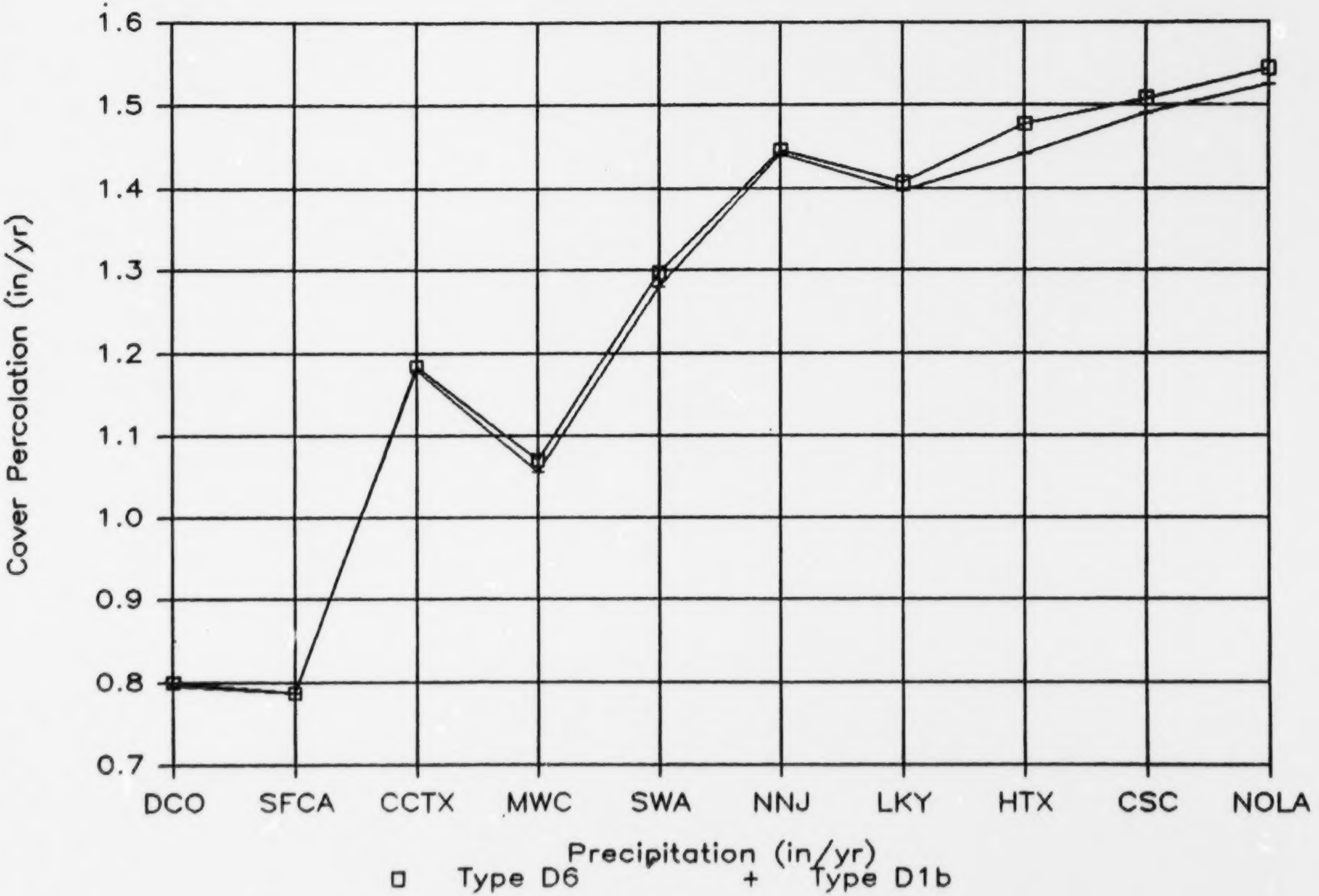


FIGURE 21

Cover Type D1a

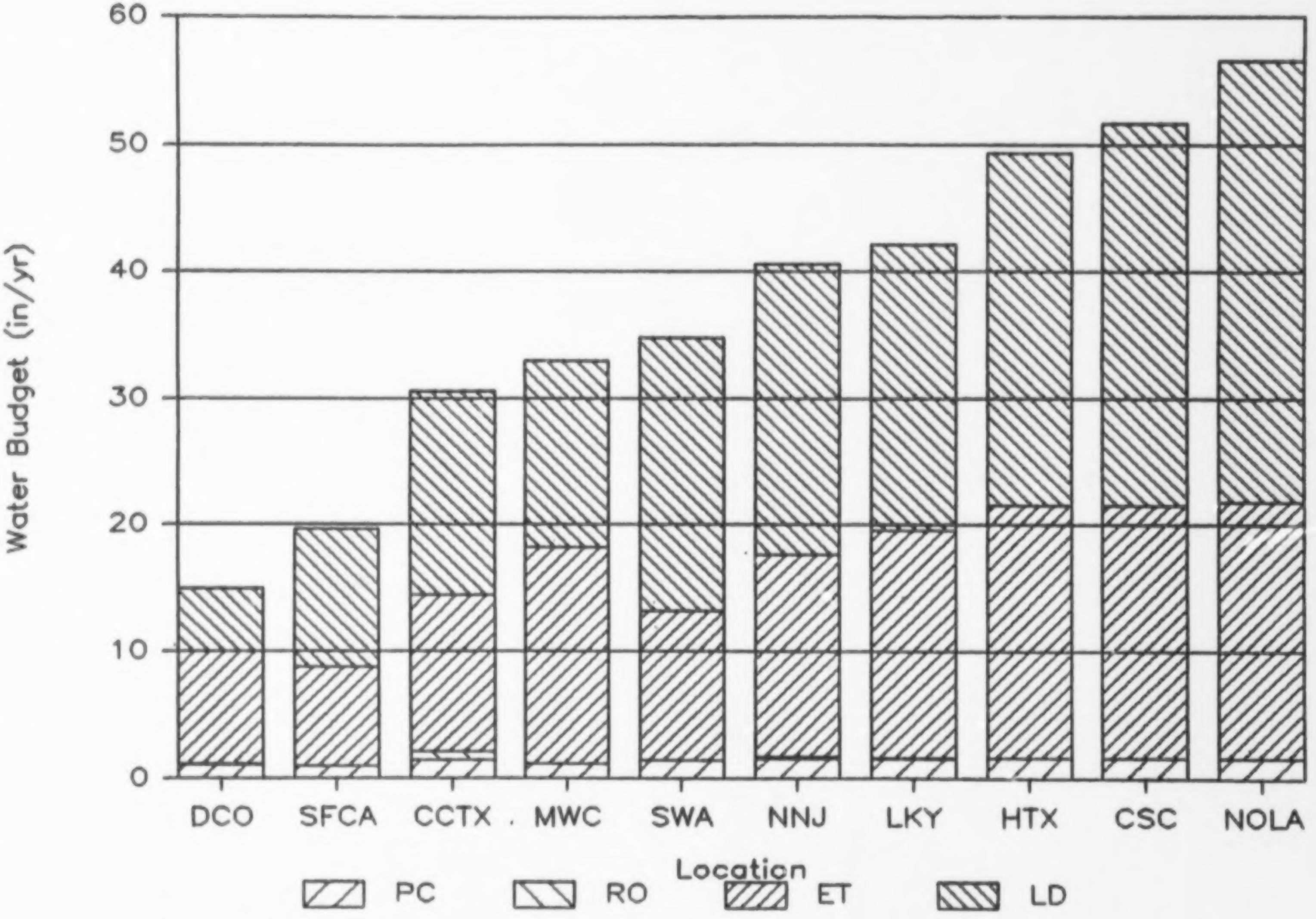


FIGURE 22

Cover Type D1b

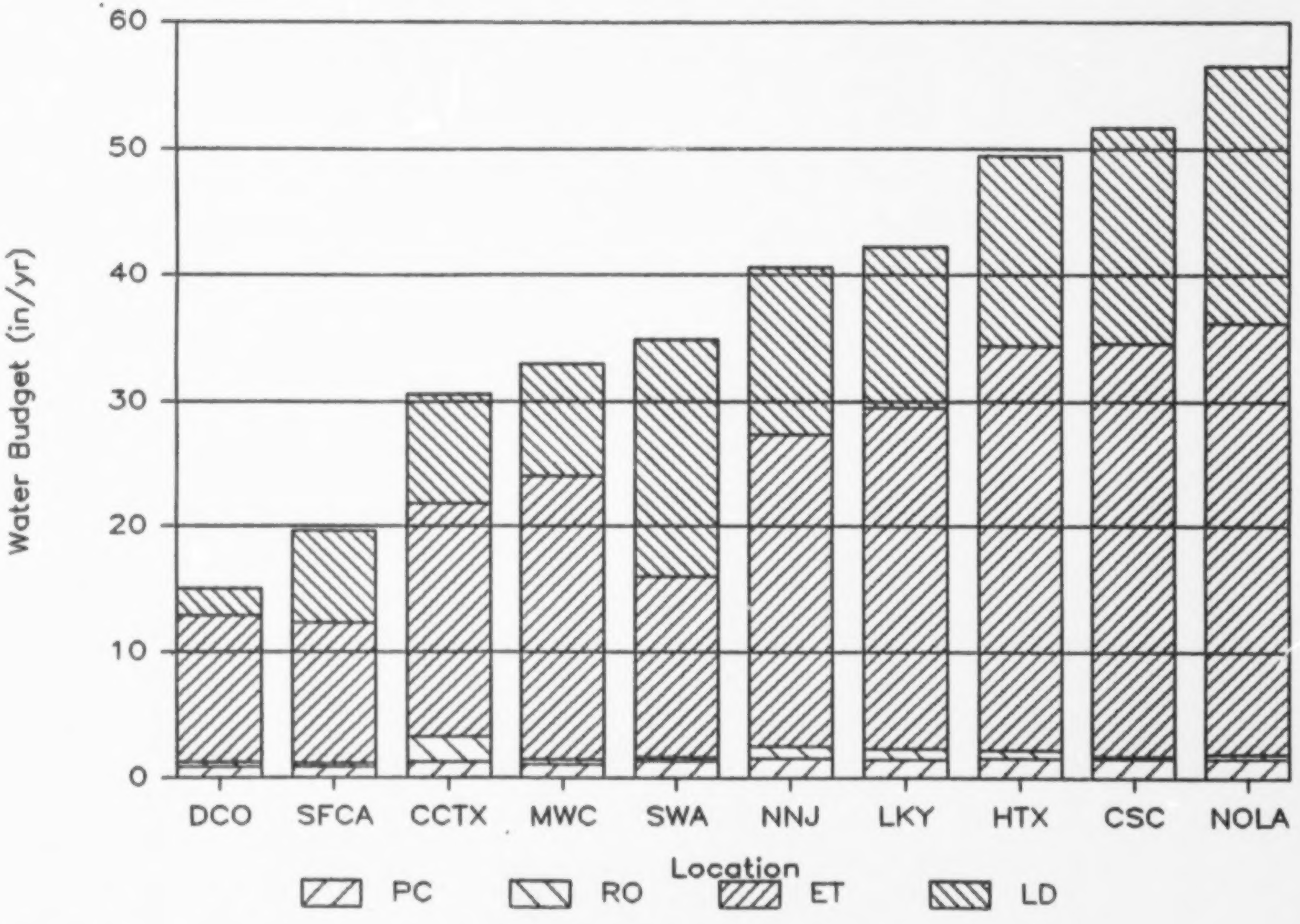


FIGURE 23

Cover Type D1f

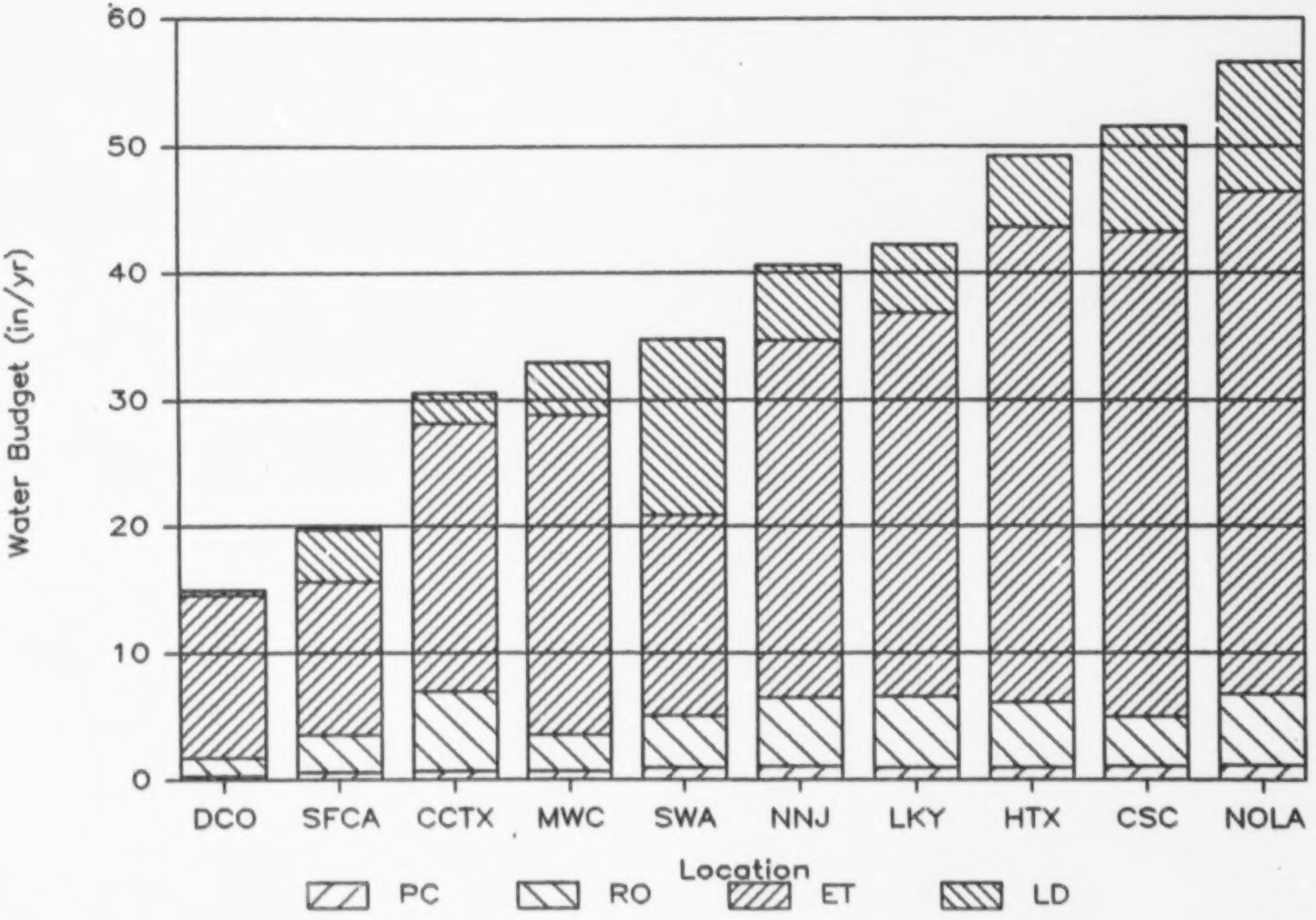


FIGURE 24

Impact of VP Layer Composition

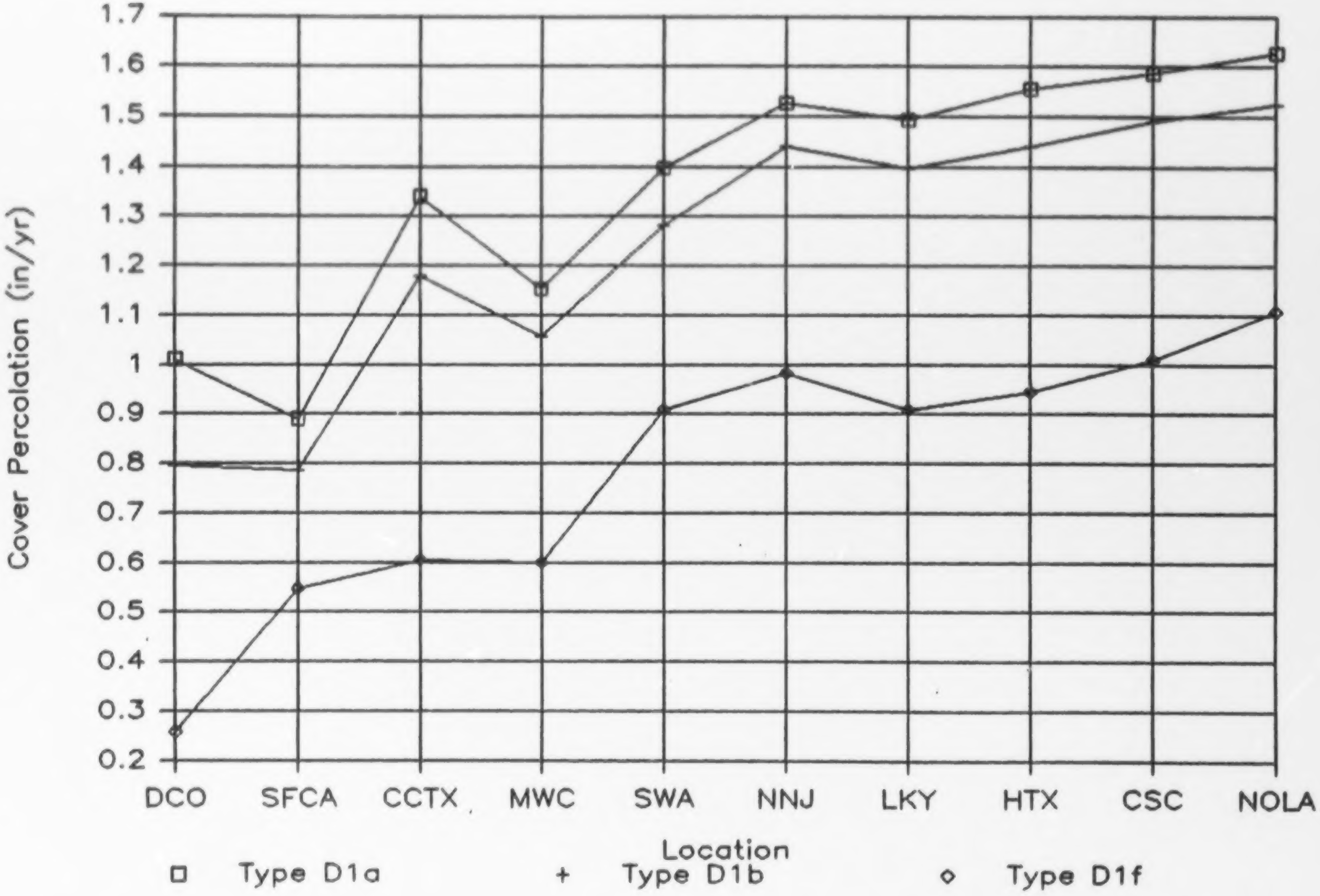
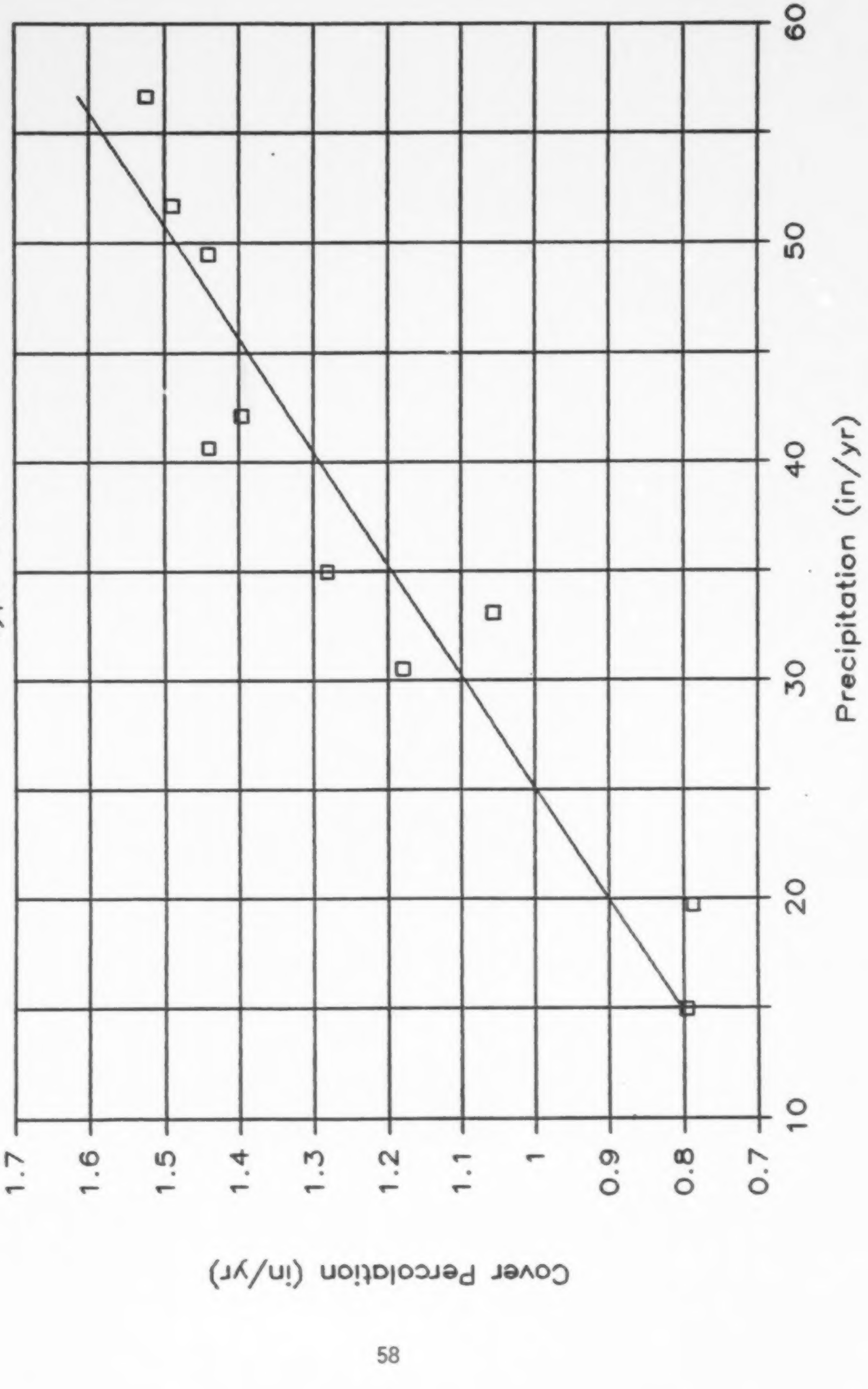


FIGURE 25

Precipitation vs. Cover Percolation

Type D1b



percolation versus precipitation for cover type D1b. The variation in cover percolation is explained fairly well by the variation in precipitation for this cover type.

The effect of runoff curve numbers on hydrologic performance was also tested. The runoff curve number (RCN) is used in determining the amount of runoff produced by the cover.

The HELP Model supplies a default value for the runoff curve number for a given cover design, based on the vegetation and soil type of the surface layer. Table 4 shows the default runoff curve numbers supplied by the HELP Model for type 5, 10, and 15 soils for the range of vegetation types specified in the Model. The HELP Model also allows the user to optionally override the default value of the runoff curve number, by manually selecting a value (ranging from 15 to 100) for a given cover design.

The effect of the runoff curve number was tested by analyzing runoff and cover percolation at the ten cities for: (1) Type D1b, using the default runoff curve numbers; (2) Type D1b, using a manually selected RCN value of 40; and (3) Type D1b, using a manually selected RCN value of 90. The grass types shown in Table 2 were used for all three cover designs in this series of runs.

The results of this series of runs are shown in Figures 26 and 27. Figure 26 indicates that runoff is reduced to zero for all ten cities when a runoff curve number of 40 is used. Based on water balance considerations, one might expect this to result in an increase in cover percolation. However, Figure 27 shows that cover percolation is nearly identical for Type D1b using default

FIGURE 26

Impact of Runoff Curve Numbers on RO

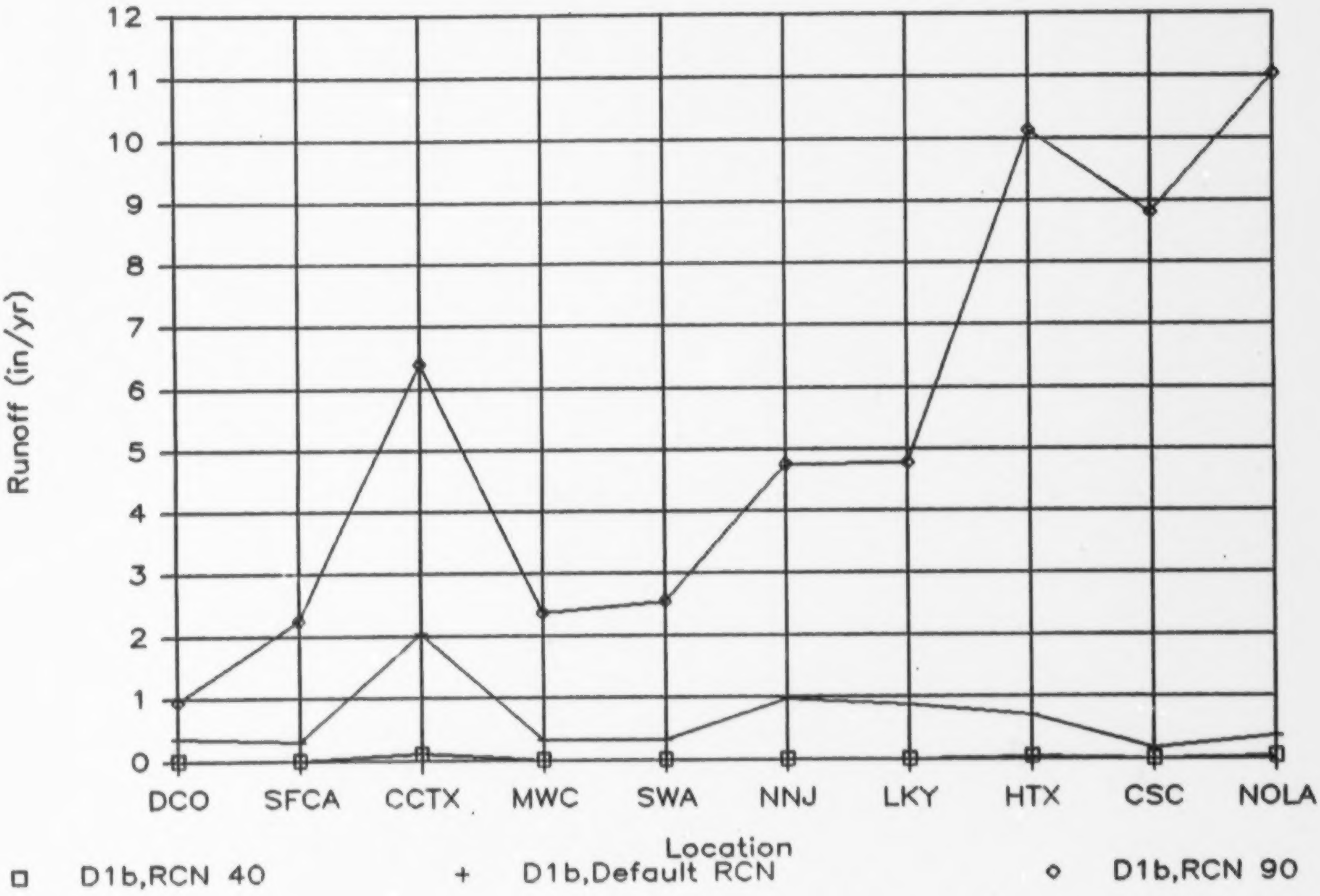
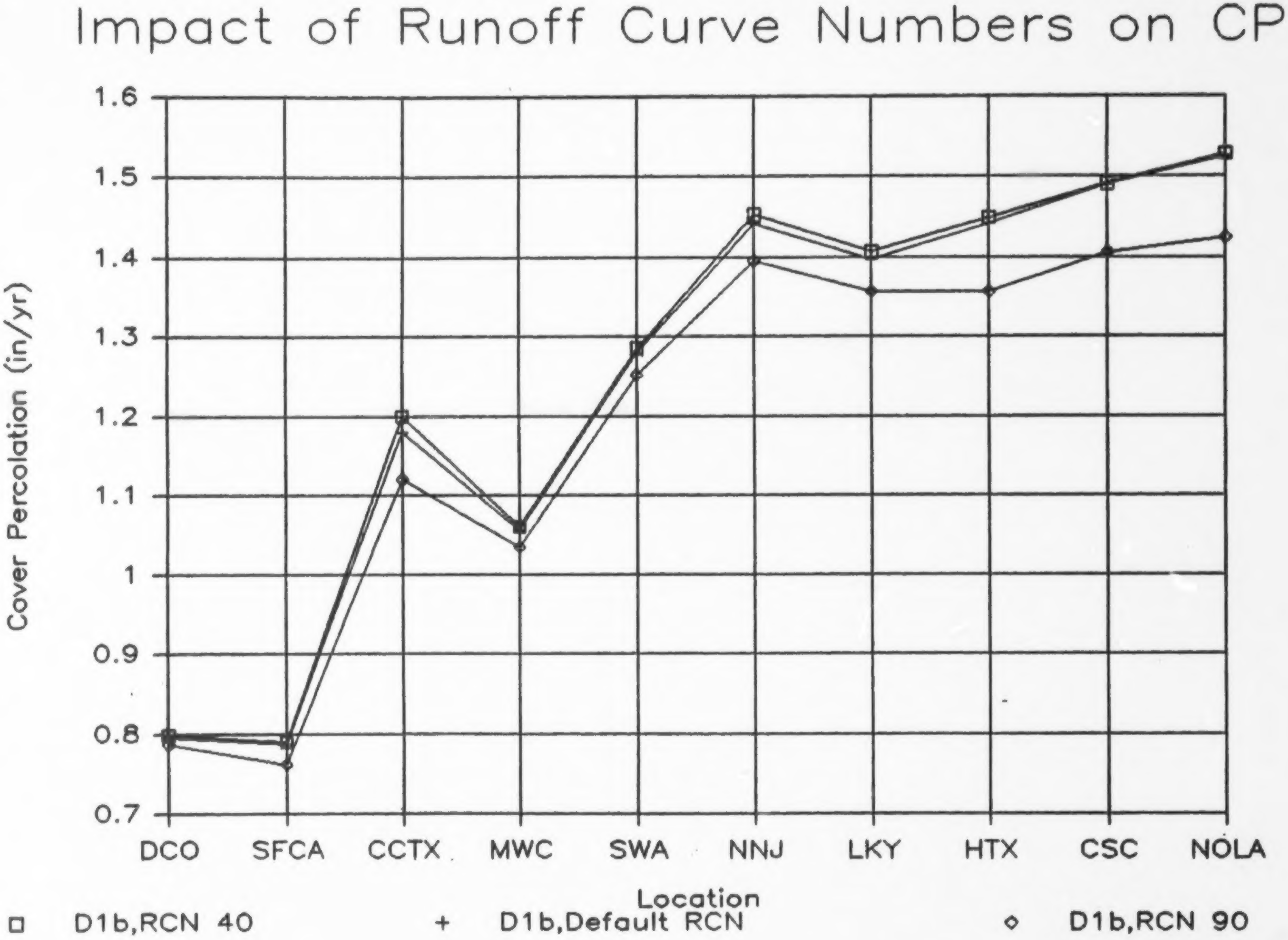


FIGURE 27


Impact of Runoff Curve Numbers on CP
Cover Percolation (in/yr)
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
DCO
SFCA
CCTX
MWC
SWA
NNJ
LKY
HTX
CSC
NOLA
Location
□ D1b,RCN 40
+ D1b,Default RCN
◇ D1b,RCN 90

curve numbers, and for Type D1b using a curve number of 40. This is because the decrease in runoff that results when a curve number of 40 is used is offset by increases in both lateral drainage and evapotranspiration.

Figure 26 indicates that runoff is greatly increased for most of the 10 cities for Type D1b with an RCN of 90, compared to Type D1b with the default curve number. Here, one might expect a decrease in cover percolation based on the water balance equation. Figure 27 shows that cover percolation is decreased from 0.01 inches for Denver to 0.1 inches for New Orleans when an RCN of 90 is used instead of the default value. However, evapotranspiration and lateral drainage are also decreased when runoff is increased, and therefore the reduction in cover percolation reflects only a portion of the increase in runoff.

In summary, changes in runoff due to different values of the runoff curve number are divided between the three other outputs of the water balance--evapotranspiration, lateral drainage, and cover percolation.

LD Layer

Figure 28 shows the effect of the thickness of the lateral drainage layer. It compares cover percolation for a D1b cover, which has a 24 inch LD layer, and a D2 cover, which is identical to a D1b, except with a 12 inch LD layer. There is no significant difference in cover percolation for the two covers in the 10 test cities. Other outputs (runoff, evapotranspiration, lateral drainage) were also very close for the two covers.

FIGURE 28

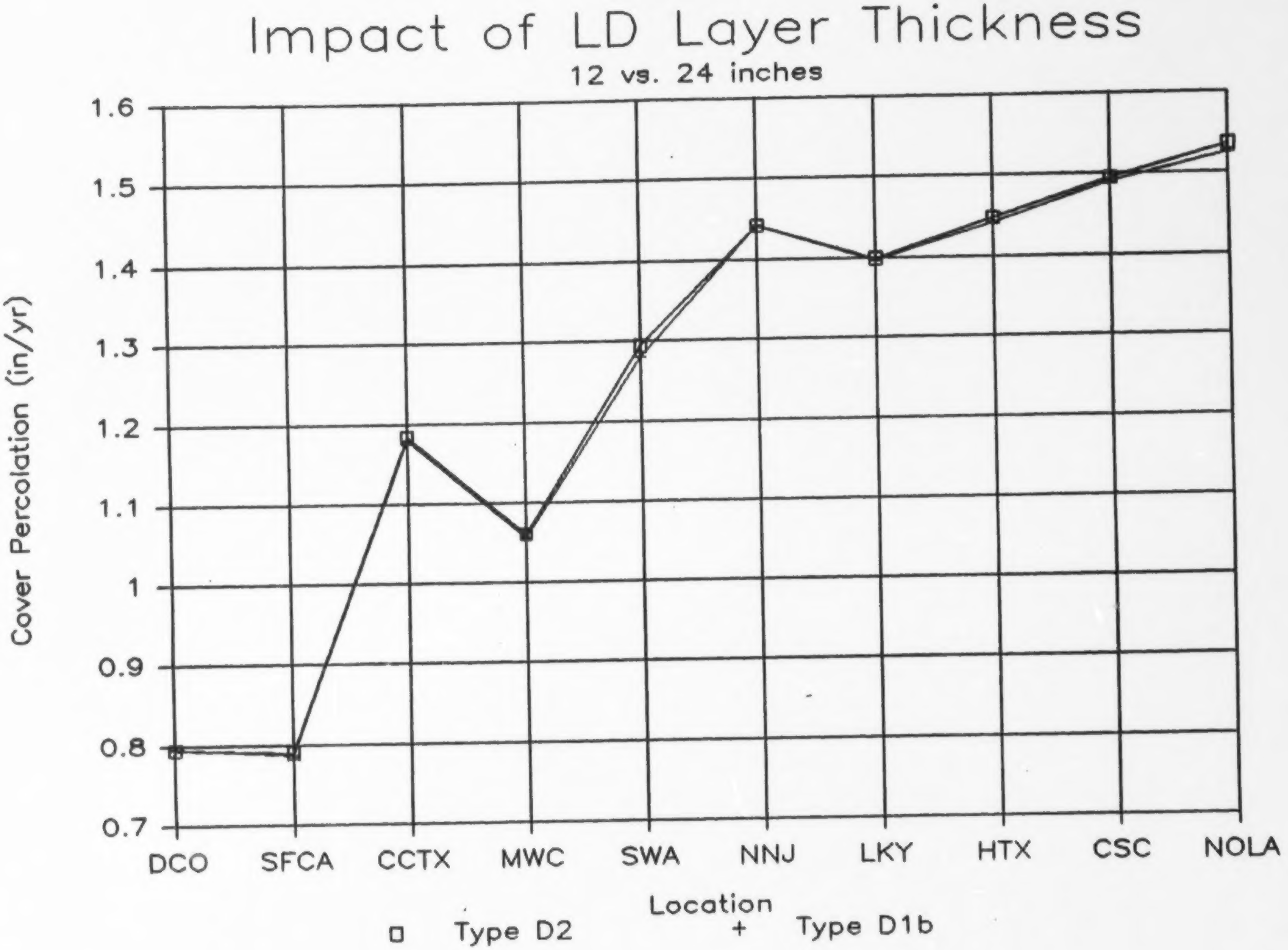

Impact of LD Layer Thickness
12 vs. 24 inches
Cover Percolation (in/yr)
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
DCO
SFCA
CCTX
MWC
SWA
NNJ
LKY
HTX
CSC
NOLA
Location
□ Type D2
+ Type D1b

Figure 29 compares cover percolation for Types D1b, which uses soil type 3 (hydraulic conductivity 6.62 in/hr) for the lateral drainage layer; D4a, which is the same as D1b, except with soil type 1 (hydraulic conductivity 11.95 in/hr) for the drainage layer; and D4b, which is the same as D1b, except with a manually entered soil type (hydraulic conductivity 1.41 in/hr) for the lateral drainage layer. Percolation for Type D4a is approximately 0.1 to 0.2 inches less than for Type D1b in the 10 cities. Other outputs (runoff, ET, lateral drainage) appear to be very similar for Types D4a and D1b. Percolation for Type D4b is approximately 0.4 to 0.75 inches greater than for Type D1b. Lateral drainage is 0.5 to 1.5 inch greater for Type D1b than for Type D4b.

The impact of slope of the lateral drainage layer on cover percolation was tested by making a series of runs for Cover Type D1b at Lexington,Kentucky, in which the slope was varied by 1 per cent intervals from 0 to 10 per cent, while holding all other parameters constant. The results of these runs are shown in Figure 30. There is roughly a 3 to 5 per cent decrease in cover percolation for each 1 per cent increase in slope.

The effect of drain spacing was tested by two series of runs for Type D1b at Lexington. In the first series, the drain spacing was varied from 200 to 25 feet in increments of 25 feet. The results, shown in Figure 31, indicate about a 3 to 9 percent decrease in cover percolation for each 25 foot decrease in drainage spacing. In the second series, spacing was varied from 2000 to 200 feet in increments of 200 feet. The results are shown

FIGURE 29

Impact of LD Layer Permeability

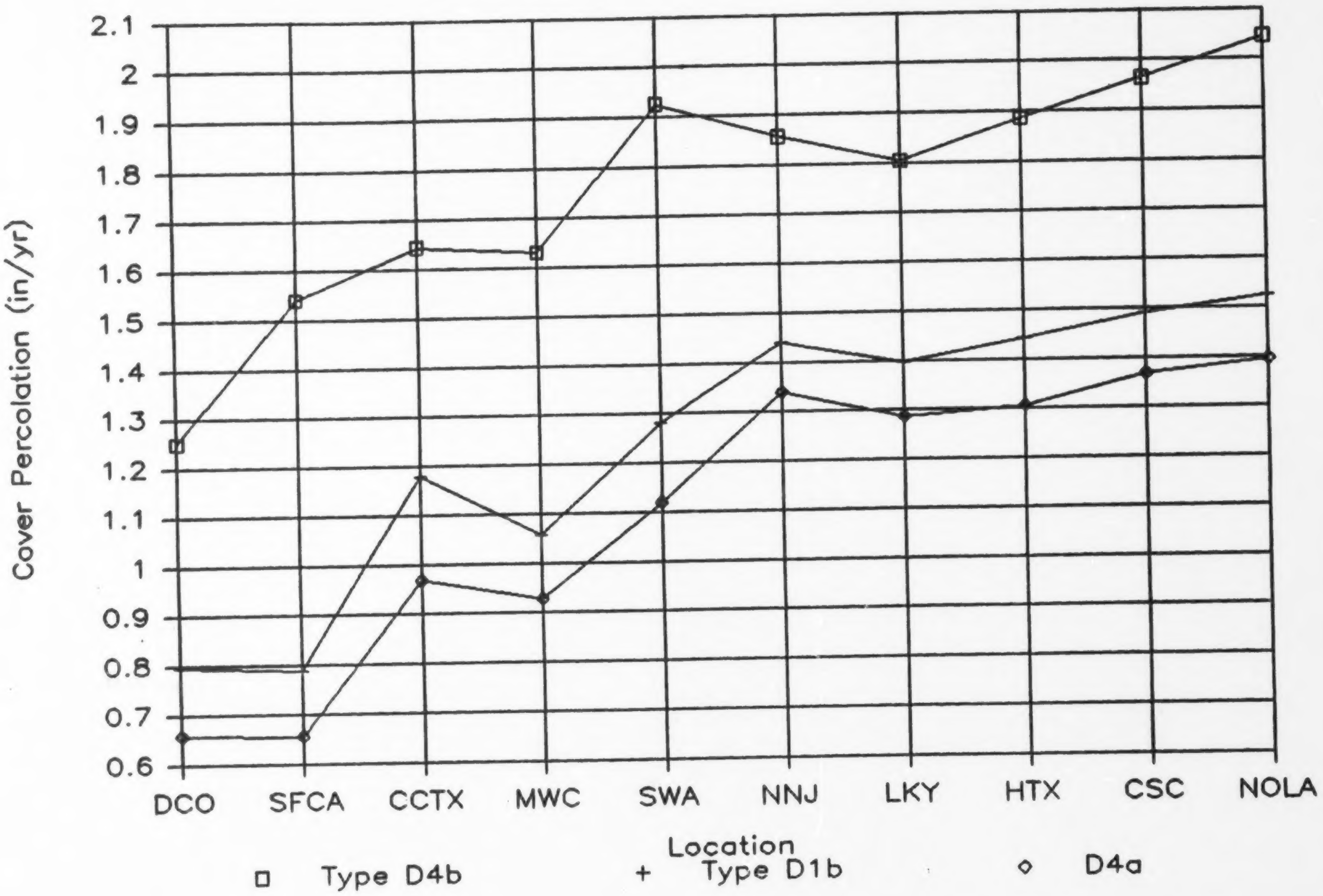


FIGURE 30

Impact of Drainage Slope

Lexington, Kentucky

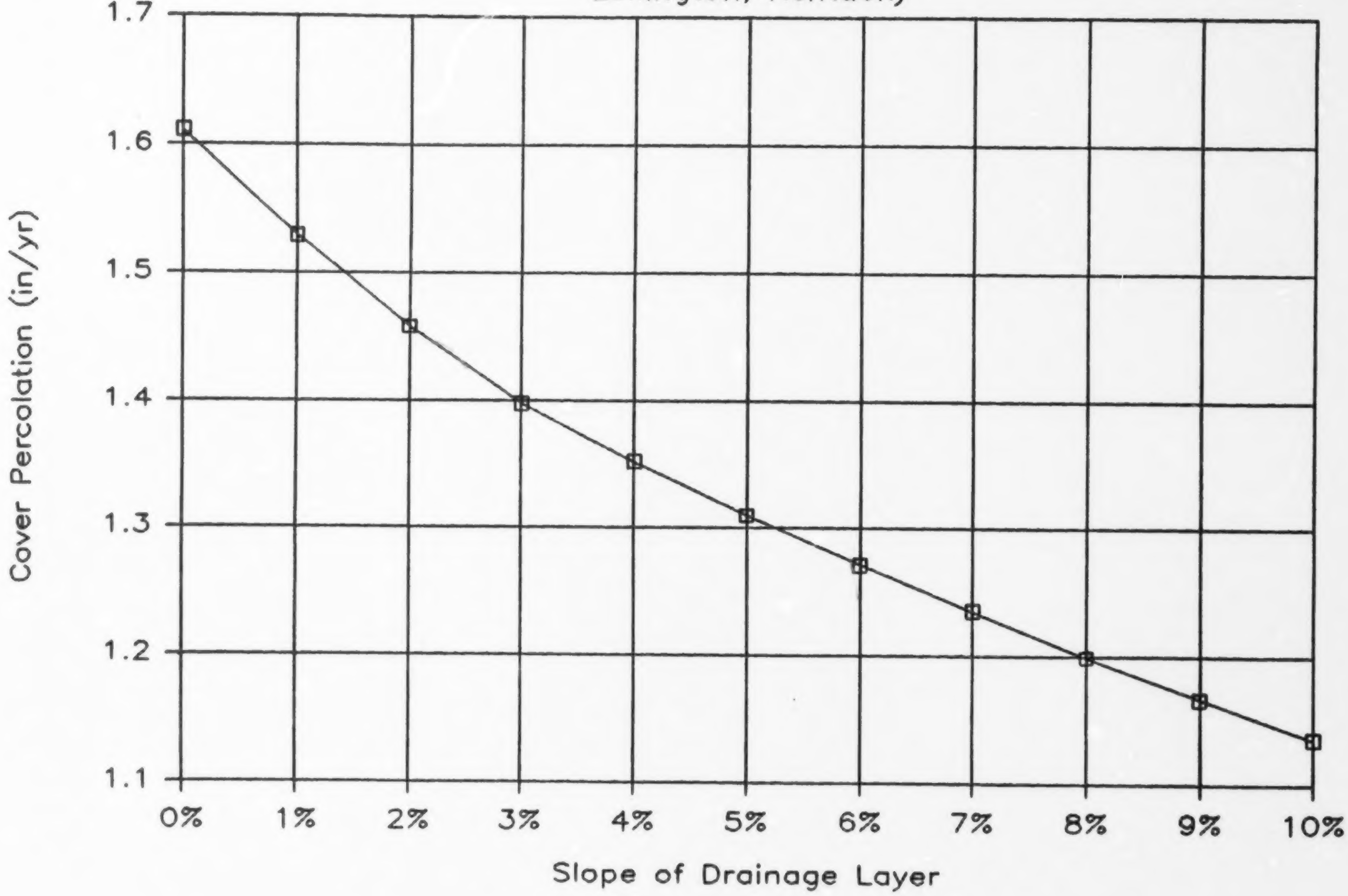
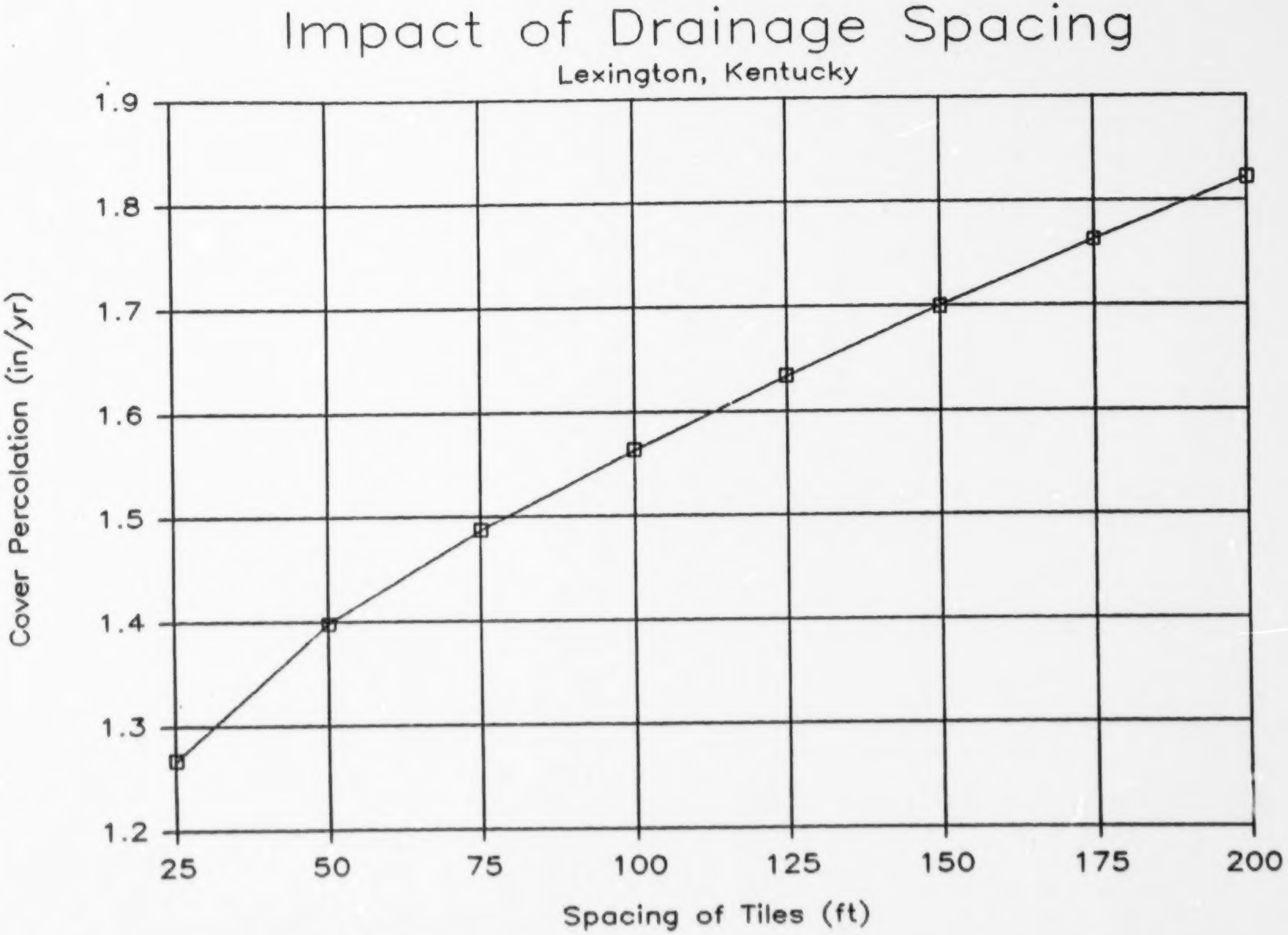


FIGURE 31


Impact of Drainage Spacing
Lexington, Kentucky
Cover Percolation (in/yr)
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
25
50
75
100
125
150
175
200
Spacing of Tiles (ft)

in Figure 32. (A drainage layer with a value for spacing equal to or greater than the maximum linear dimension of the landfill can be used to simulate a drainage layer with no drain tiles.)

The impact of slope and spacing of the drain tiles on cover percolation are similar for other cities.

Barrier Layer

Figure 33 shows the impact of the thickness of the barrier layer on cover percolation. The graph compares the cover percolation for cover Type D1b, which has a 24-inch barrier, and Type D3, which is the same cover with a 12-inch barrier. The graph shows an increase in cover percolation for Type D3 ranging from 3 percent for Denver to 15.5 percent for Seattle and New Orleans.

Figure 34 shows the effect of soil type of the barrier layer on cover percolation. It compares cover percolation for Type D1b (which uses soil type 20, with a hydraulic conductivity of 0.000142 in/hr, in the barrier layer) with percolation for Type D5a (same as D1b, except with a soil with a hydraulic conductivity of 0.0142 in/hr in the barrier), Type D5b (same as D1b, except with a soil with a hydraulic conductivity of 0.00142 in/hr in the barrier), and Type D5c (same as D1b, except with soil type 21, with a hydraulic conductivity of 0.0000142 in/hr, in the barrier). The graph shows that reducing the hydraulic conductivity of the barrier soil by a factor of 10, causes a significant reduction in cover percolation for the ten cities. The amount of the reduction generally increases as average annual

FIGURE 32

Impact of Drainage Spacing: 200 to 200(

Lexington, Kentucky

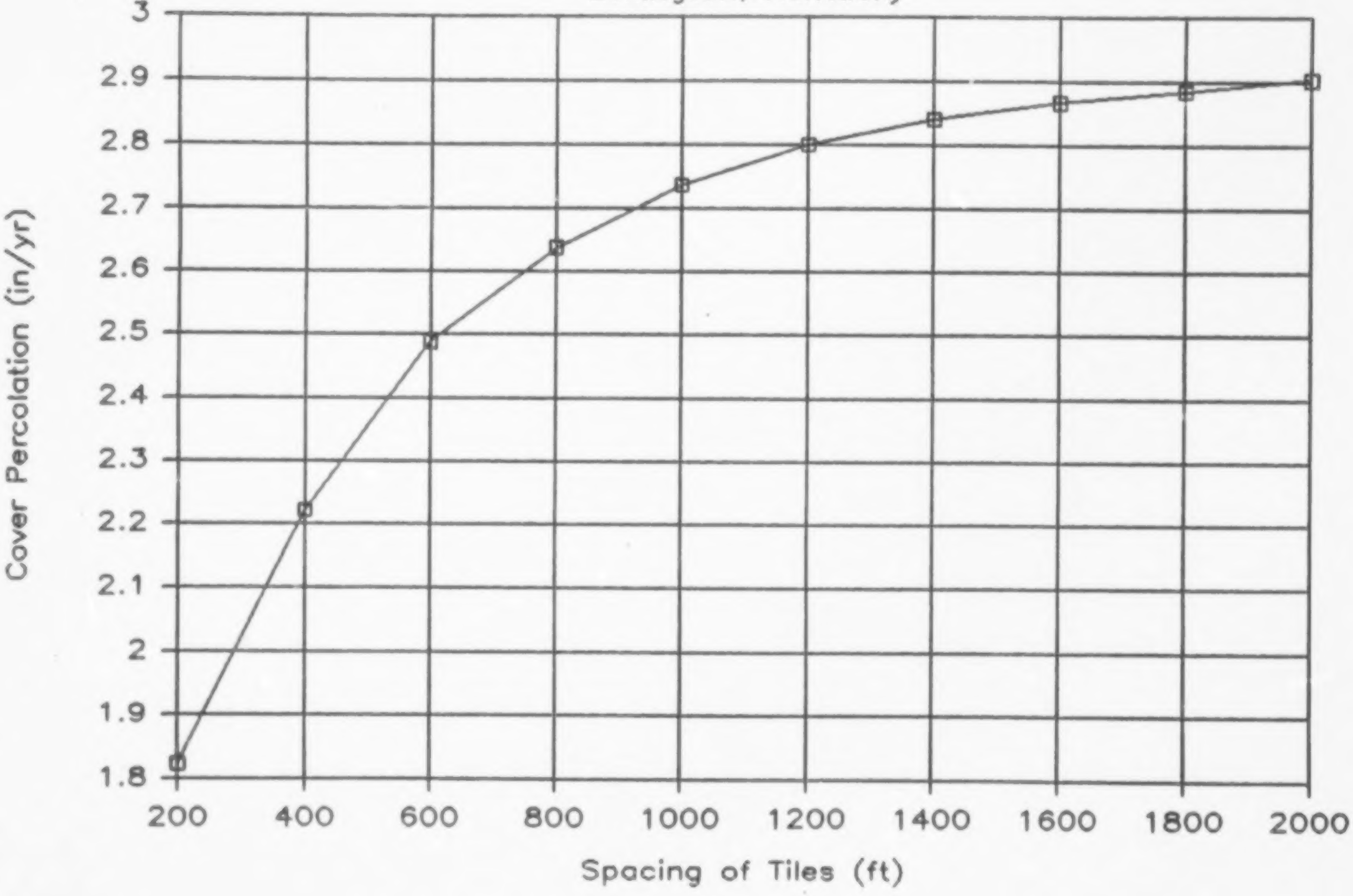


FIGURE 33

Impact of Barrier Thickness

12 vs. 24 inches

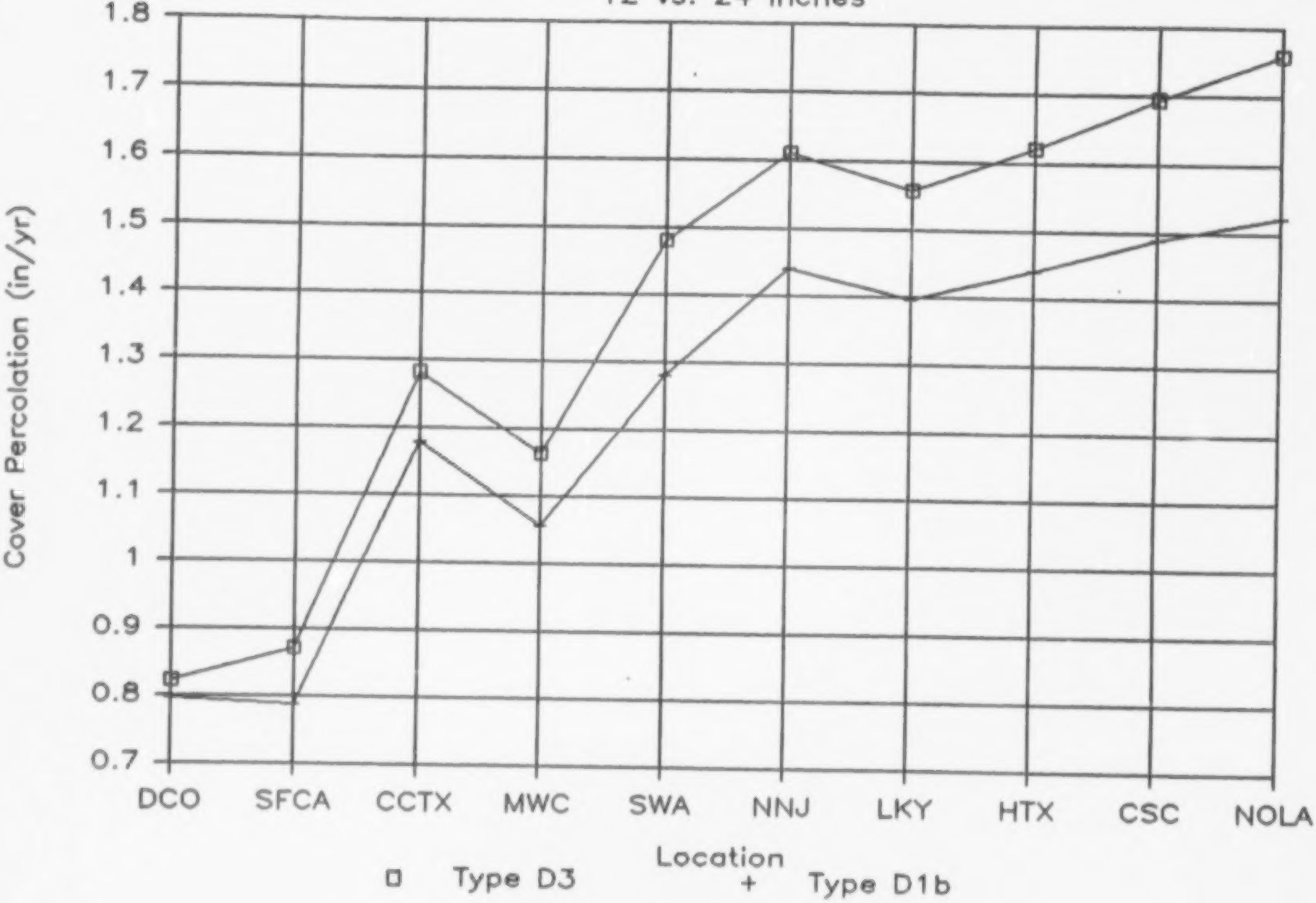
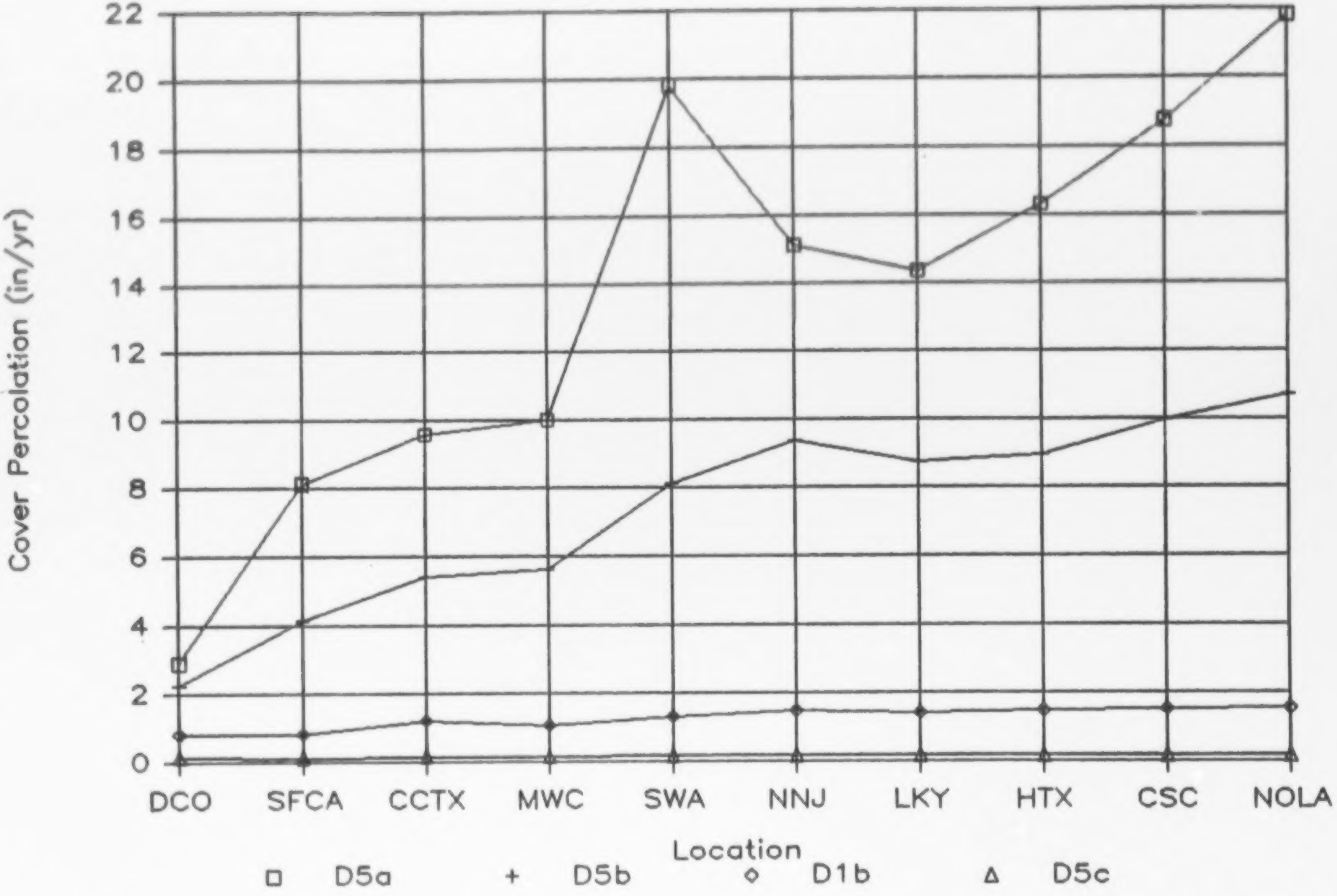


FIGURE 34

Impact of Barrier Permeability on CP



precipitation increases. (Note: A hydraulic conductivity of 0.000142 in/hr is equal to 0.0000001 cm/sec).

Figure 35 is a more detailed comparison of cover percolation for Types D1b (barrier hydraulic conductivity of 0.000142 in/hr) and D5c (barrier H.C. of 0.0000142 in/hr). It indicates that for these two types, a factor of 10 reduction in hydraulic conductivity causes a reduction in cover percolation ranging from a factor of 6.7 for Denver, to a factor of 9.9 for New Orleans. Figures 34 and 35 indicate that hydraulic conductivity of the barrier layer soil is one of the most critical parameters in cover design.

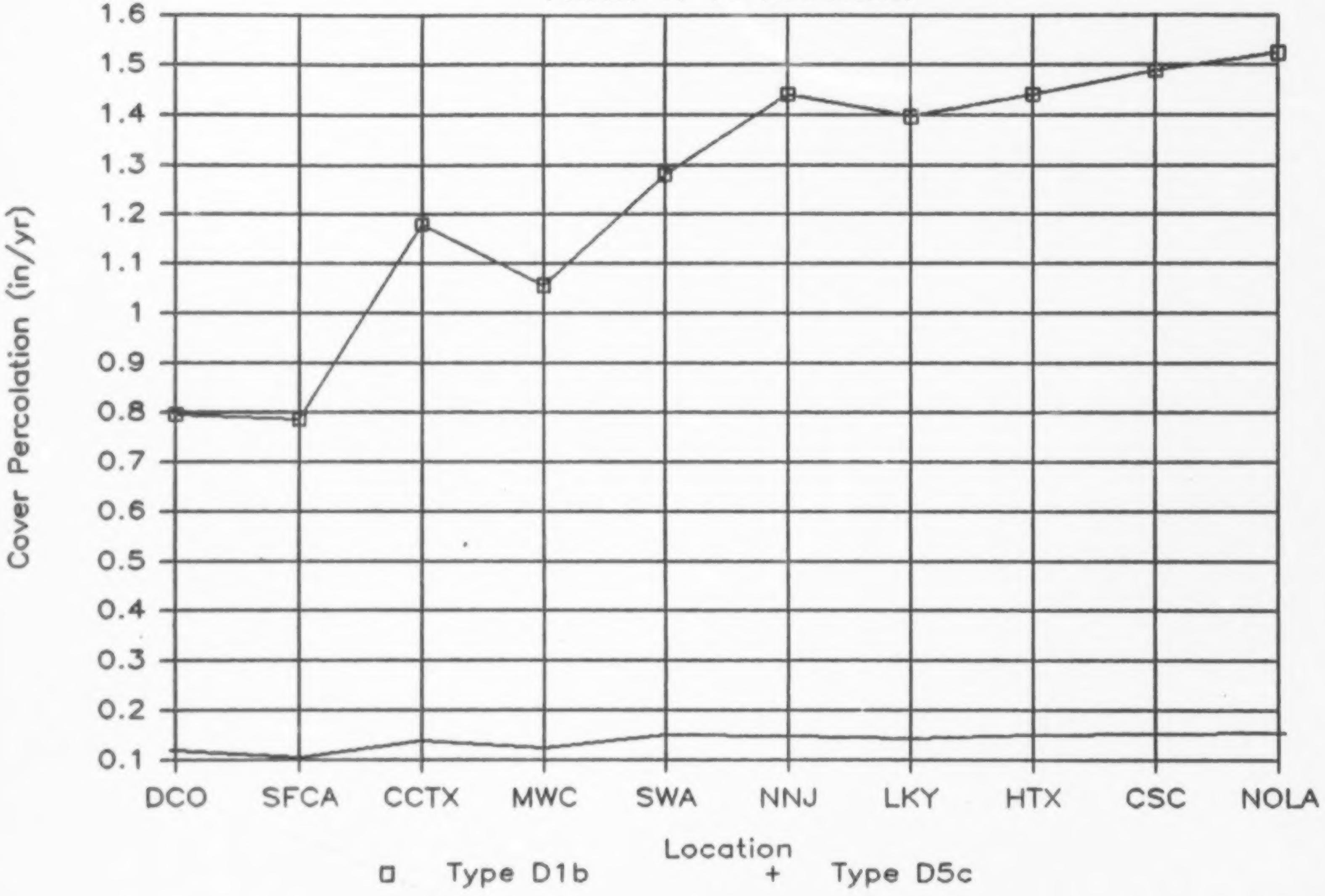
STANDARD DEVIATIONS OF OUTPUTS FOR COVER TYPES B1C AND D1B

Appendix D gives the sample standard deviations for the annual values of precipitation, runoff, evapotranspiration, cover percolation, and lateral drainage for cover types B1c and D1b for the ten cities in Table 2. The number of annual values used to compute the standard deviation for each city is the same as the number of years of record shown in Table 3.

FIGURE 35

Impact of Barrier Permeability on CP

Factor of 10 Reduction



SECTION 6

OTHER SITE-SPECIFIC CONSIDERATIONS

ANIMAL AND VECTOR CONTROL

Municipal waste landfills offer potential food and shelter resources for birds, burrowing animals (such as rats and badgers), and vectors (flies, mosquitos). Many cover designs can minimize or prevent this type of nuisance. The suitability of cover designs for bird, animal, and vector control is broadly discussed below; Table 5 evaluates the suitability of the recommended cover designs.

Bird Control at Landfill Sites

Birds are attracted to landfills by the availability of food. It is essential that the landfill cover is well packed and thick enough to prevent digging by birds.

Burrowing Animal Control

Burrowing animals dig tunnels into landfills in search of food and shelter. These tunnels are extremely damaging to the hydraulic barrier of the cover system. A maze of tunnels provides for surface water infiltration and cover percolation, leading to increased leachate production. Burrowing animals may also bring contaminated soil and debris to the surface, increasing public health hazards.

TABLE 5. SUITABILITY OF RECOMMENDED COVER DESIGNS FOR ANIMAL AND VECTOR CONTROL

FUNCTION	COVER DESIGNS A1	B1c	C6a	D1b
Prevent rodents from burrowing or tunneling	P	P	G	G
Keep flies from emerging	G	G	E	E
Minimize attractiveness to birds	G	G	E	E

E = Excellent
G = Good
F = Fair
P = Poor

Two main procedures are used when designing cover systems to discourage burrowing animals: (1) use cover soils with low shear and tensile strengths which possess low arching potential and favor burrow instability (General Electric Co., 1975; Lutton, Regan, & Jones, 1979); and (2) tightly pack objects in the animal's path which will block its progress (EPA, 1985). The first method appears to be more practical and effective.

For the most part, tensile strength and arching potential increase as percentages of clay and silt sized particles are increased in mixtures. Therefore, dry, loose, clean gravels and sands are more effective in deterring burrowing animals.

Vector Control

Flies are attracted by the availability of food and breeding areas at municipal landfills. Compacted, strong, dense, well-graded soils of a minimum depth of six inches will discourage fly larvae emergence (General Electric Co., 1975; American Society of Civil Engineers, 1976).

Mosquitos are attracted to stagnant water bodies which serve as hatcheries for eggs. The surface of the landfill cover should be well-graded to discourage the development of such areas (American Society of Civil Engineers, 1976).

SUBSIDENCE

Overview

Subsidence is a major concern in the design and operation of hazardous waste and sanitary landfills. Subsidence is defined as "the settling or sinking of the land surface due to any of several factors, such as decomposition of organic material, consolidation, drainage, or underground failure." (EPA, in press, page E-28).

Differential subsidence or settling of the waste layer in a landfill is a major threat to the integrity of the landfill cover. Subsidence can cause cracking or deformation of the hydraulic barrier layer, disrupting its function as a barrier to percolation; it can also disrupt the integrity of the drainage pipe system in the lateral drainage layer. Finally, subsidence can adversely affect the surface drainage of a cover by causing depressions and irregularities in the surface layer.

Occurrence

Consolidation of the waste layer in a landfill, leading to subsidence, occurs when the forces acting on the waste layer are in disequilibrium. Subsidence may occur due to processes occurring in the waste layer, such as the deterioration of waste packages or containers, collapse of soil bridges between objects, movement of fine material into larger void spaces, strength losses due to chemical and biological reactions, and material losses caused by decomposition and gas formation.

Some of the factors affecting the rate and magnitude of subsidence in the waste layer are the stress history of the layer, its initial density, and the magnitude of pressure applied to the layer. Also important are rainfall and temperature, which affect the decomposition of materials in the layer.

Yen (1975) collected up to 9 years of data on subsidence at three landfills in California which contained mostly municpal solid wastes. For these sites, he found that the rate of settlement appears to decrease in linear proportion to the log of the median fill age and that settlement rates increase with the depth of the waste layer, up to a depth of about 100 feet. He estimated total post-construction settlement of the study sites to be 4.5 to 6 percent of the total fill depth. His data indicated that the total duration of the settlement process may exceed 250 months.

Techniques for Controlling Subsidence

Techniques for controlling subsidence in landfills are still in the developmental stage. Techniques can be divided into two categories: (1) operations performed to control subsidence in the waste layer and (2) features of the cover layer which are intended to minimize the effects of subsidence.

Subsidence in the waste layer can be reduced by increasing the ratio of daily soil cover to waste, compaction, the use of soil additives or cements, and recirculation of leachate through the waste layer (prior to cover installation) to hasten decomposition.

The cover layer itself can be made less susceptible to subsidence by creating a stable foundation or buffer layer between the waste layer and the cover. This foundation layer would consist of 24 inches or more of compacted, coarse-grained material, such as sand or gravel. This layer provides a stable base for the cover layer. It also protects the cover from puncture by sharp or uneven surfaces at the top of the waste layer. The foundation layer does not prevent subsidence; however, it can help to mitigate its effects, if not too severe. This layer can also serve as a channel for lateral gas migration in a gas control system.

Another way to make the cover less susceptible to subsidence is to increase the thickness of individual layers in the cover, particularly the foundation layer and the hydraulic barrier layer. More research is needed on actual landfill performance to determine the optimum thickness of these layers for different conditions. A good rule of thumb is that both of these layers should be at least 24 inches where subsidence is expected.

A third technique to control subsidence is to incorporate the capability for future repairs in the cover design, if severe subsidence is anticipated.

Suitability of Recommended Covers

Cover Type B1c, the one-layer cover, is not as susceptible to damage from subsidence as the more complex cover types. This cover could be made more resistent to subsidence damage by increasing the thickness of the layer.

Cover Type A1 is susceptible to subsidence damage because of the relatively thin layers: a 12-inch barrier layer and a 6-inch surface (VP) layer. This cover could be made more resistent by increasing the thickness of the barrier layer to 24 inches, and/or by the addition of a foundation layer.

Cover Types C6a and D1b are susceptible to subsidence damage because both have a hydraulic barrier layer and a lateral drainage layer containing a system of drainage pipes. These covers can be made less susceptible by including a foundation layer, by increasing the thickness of the hydraulic barrier layer, and by providing access for repair of the drainage system if necessary.

CONTROLLING GAS PRODUCTION AND MOVEMENT

General Information

Gases and vapors are produced by waste materials at landfill sites by (1) decomposition of organic matter, (2) chemical reactions resulting from two or more reactive materials coming into contact, or (3) the evaporation of volatile substances.

Methane

Organic substances in municipal landfills undergo anaerobic decomposition by microbial fermentation after covering, producing various gases and organic residues. Methane (CH_4) and carbon dioxide (CO_2) can comprise as much as 90 percent of the gases produced by decomposition of organic materials. The volume and composition of gas produced is dependent on the percentage and type of biodegradable material in the landfill and the presence of water, which is needed to promoted anaerobic decomposition. According to Esmaili (1975), the chemical reaction can be represented as:

$$C_aO_bH_cN_dS_e \quad \xrightarrow[\text{Bacteria}]{\substack{\text{Anaerobic} \\ \text{Decomposition}}} \quad wCO_2 + xCH_4 + yNH_3 + zH_2S \text{ humus}$$

Control of methane gas is the major concern (EPA, 1979). Methane is colorless and odorless, but highly explosive in concentrations of 5 to 15 percent in oxygen (Nobel, 1976). There is little danger of a landfill exploding, since there is virtually no oxygen present when methane is produced. However, methane diffuses along the path of least resistance and may migrate laterally from a landfill site and accumulate in nearby structures (such as basements), where it could easily reach critical concentrations and pose a hazard (Noble, 1976). Methane control techniques are aimed at limiting its production and stopping lateral subsurface migration by venting the gas to the atmosphere where natural mixing reduces the concentration to safe levels.

The degree of permeability of the final cover design will determine the onset and rate of methane production. The cover should be as impermeable as possible to reduce infiltration, preventing the buildup of excess moisture needed to promote anaerobic decomposition (Noble, 1976).

Figure 2 compares cover percolation of the recommended cover designs at each location. Cover types D1b, A1, and C6 effectively reduce methane production by reducing infiltration. Cover type B1c performs poorly in regard to reducing cover percolation in all locations except Denver, Colorado.

Volatile Toxics

Many gases formed by vaporization of volatile liquids or by chemical reactions are toxic. With volatile toxic vapors, it is important to control both lateral subsurface movement and atmospheric emissions. Gas collection and emission control procedures are mandatory at sites where volatile toxics occur.

Designing for Control of Gas Migration

Moist, fine-grained soils and saturated coarse-grained soils are natural barriers to gas migration (EPA, 1979). Conversely, clean, dry gravels and sands are permeable and promote the flow and venting of decomposition gas. Cover designs which contain a clay barrier layer (such as D1b, A1, and C6a) inhibit the formation of gas, but also prevent the gas from migrating vertically and naturally venting through the surface of the landfill. It is important to prevent lateral movement of gas beyond the landfill boundaries by venting the gas and/or collecting it at the landfill site. The venting system must be designed in such a way that it does not impair the ability of the final cover to reduce infiltration.

The design of a gas control system is highly site-specific, and is based on the type of wastes present, depth of fill, subsurface geology of the site and adjacent areas, soil permeabilities, and gas concentrations (EPA, 1985). Types of gas control systems include gas drainage layers with vents, vertical pipe vents, trench vents, and induced exhaust gas extraction systems. These systems are briefly described below in the following paragraphs:

A gas drainage layer is placed on the lower side of a barrier layer to intercept gases rising from the waste layer and convey them to vents. A secondary function of the gas drainage layer is to provide a level base for the barrier layer. The gas drainage layer usually consists of clean, dry gravel. Pipe vents or gravel trench vents are constructed down into the gas drainage layer to vent off the gas.

The gas drainage layer can be obstructed by the growth of slimes produced during anaerobic decomposition, which coat the gravel particles. The larger the pore sizes in the gas drainage layer, the longer it takes a buildup of slime to block the pores completely. Thus, coarser materials are preferred for a gas-drainage layer (EPA, In Press).

Pipe vents are simply perforated pipe installed vertically or laterally in a landfill for collecting gases or vapors. They may either be installed in landfills alone, or in conjunction with gas drainage layers, trench vents, and/or induced gas exhaust or extraction systems. Pipe vents used alone are placed at strategic locations where gas probe sampling indicates a high concentration of gas. Pipe vents used alone are not an effective means of controlling lateral gas migration (EPA, 1985). These vents are effective only when used in situations where there is little lateral migration, and where gases migrate freely to the collection area.

A permeable gravel-filled trench can be an effective system to control lateral gas migration at a landfill site, particularly if the trench extends around the perimeter of the landfill site and extends to a depth at least two feet deeper than the landfill base (Noble, 1976). If the trench is situated in permeable soil, it is necessary to use an impermeable barrier such as a synthetic membrane or a layer of nonswelling clay, on the outside of the trench. It is important that there is a surface water drainage channel between the trench and the landfill, and that the trench is raised and slopes toward the drainage channel. This prevents runoff or eroded materials from flowing into the trench and blocking the migration of the gas (Nobel, 1976). Vent pipes should be installed in areas where freezing and sealing of the trench vent can occur (EPA, In Press). Coarse materials should be used in trench vents to prevent obstruction by slime.

An induced exhaust system (also called a forced ventilation system) consists of equipping a system of pipe vents with individual fans or connecting the vents to a manifold with a centralized fan or blower. The gas can then be discharged into the atmosphere, into a gas treatment system, or into a gas recovery system.

All of the landfill cover designs described in this report will require a site-specific plan to control gas production and movement. Numerous publications address control of landfill gas, and the reader is referred to the publications in the bibliography for more information on this subject.

COSTS

This information on estimated costs of the recommended cover types is intended only to provide an approximate comparison. These cost estimates are based on a conceptual design that omits many of the specific details that would be required in an actual landfill cover design. Also, very little cost information is available from actual landfill construction. Most of the cost estimates presented here are based on costs for similar construction operations. Consequently, the cost information presented here should be used with caution. Costs for an actual landfill designs should be based on the particular requirements of the design.

The cost information presented here was based on two sources: Rishel et al. (1982) and EPA (1985). Rishel et al present cost information for a number of "unit operations" and materials that can be used selectively to design a landfill or a surface impoundment. Information is included on the effects of economies of scale and regional variations on the cost of landfill design factors. Their cost information is based on mid-year 1980 estimates. Most of their information was obtained from McMahon (1979) and Means (1979), which are guides for estimating construction costs. Rishel et al. warn that their information should be used with care, since at present there is very little information available on the cost of designing "real-life" landfills, and their cost estimates are based on a number of design assumptions. EPA (1985) also presents some very useful information on the cost of landfill components.

The following is a description of the assumptions and design features used to develop the cost estimates for the recommended landfill designs presented in this report.

A landfill shaped like a rectangular solid, with a square horizontal cross-section whose sides are 200 meters long, is assumed. The area of each layer in the cover designs is assumed to be 40,000 square meters (9.88 acres). The volume of each layer is calculated by multiplying its design thickness (in meters) by 40,000 square meters. The waste layer and the intervening layers are assumed to lay below ground. The top of the surface layer is assumed to be about a foot above the general ground level, to allow for surface runoff. A life cycle of 10 years is assumed for the landfill. Maintenance costs (for drainage ditch maintenance, grass mowing, and refertilization) are estimated for one year, and then multiplied by 10 and added to the other component costs. Costs are based on mid-year 1980 estimates, and were not adjusted for inflation. Rishel et al. (1982) allowed for overhead and contingency costs in their estimates by adding 25 percent (for overhead) to the cost of each operation, and 10 to 40 percent for contingency. These additional costs were not included in the cost estimates presented here.

Cost estimates for the recommended cover designs are shown in Appendix C. The various operations and components of the designs are listed on the left side of Appendix C. The next column to the right shows the unit for which the unit costs for each operation are given. The next three columns show the low, high, and average unit costs for each operation or component. Low and high costs are taken from Rishel et al. (1982) and represent the range of costs due to regional variation.

Two columns, units and cost, are listed under each of the four recommended designs. "Units" represents the number of units of a component required for the design. For example, the number of units of sand (item 12) required for Design D1b is calculated by multiplying the thickness of the LD layer for D1b (24 inches or 0.6096 meter) by the surface area of the layer (40,000 square meters) to obtain 24,384 cubic meters. In the next column, the "cost" of sand is calculated by multiplying the number of units (24,384 cubic meter) by the average cost per unit ($19.61 per cubic meter) to obtain $478,170.

At the bottom of Appendix C, the total cost for each cover design is displayed. Two total costs were computed for each design: the first assumes the use of topsoil for the surface layer; the second assumes the use of locally excavated soil. The two total costs for design A1 are the same, based on the assumption that gravel could not be locally excavated. The total cost for cover design A1 includes the cost of a synthetic liner between the gravel VP layer and the barrier layer.

Additional information on the assumptions used for each design component is given below.

Site Preparation

Item 1 estimates costs for excavating, grading, and recontouring of the surface of the final waste layer to a depth of 0.5 meter, to create a stable base for the cover.

Item 2 estimates costs for excavating and grading a soil cover over the final waste layer, to provide a stable base for the cover. This soil cover would be 0.3 meter thick and would consist of soil excavated close to the landfill site.

Barrier Layer Installation

Item 4 estimates costs of materials and installation for a clay barrier layer. Included are the costs of hauling (within 20 miles), spreading, and compaction.

Synthetic Liner

Item 6 estimates cost of material and installation for a Hypalon liner, 30 mil thickness, bracketed with heavyweight geotextile fabric.

Drainage Layer Installation

Designs C6a and D1b contain a lateral drainage layer. A conceptual drainage system was designed to estimate costs for the drainage layer for these two designs. This conceptual design is very simplistic and omits many of the essential details that would be required in a working design. The design assumes that the clay barrier layer is crowned along the center line of the landfill, sloping toward the sides at a 3 percent slope. The design calls for sections of 4-inch diameter perforated cement pipe to be installed at 50-foot (15.24-meter) intervals. These pipe sections would be set in trenches excavated in the top of the clay barrier layer. These sections would be 100 meters long, extending from the centerline of the landfill toward each side. A total of 28 100-meter sections would be required. The trenches would have a cross-sectional area of 0.09 meter, and a length equal to the length of the pipe. The trenches would be backfilled with gravel (estimates are for 3/4 inch, screened gravel). The volume of gravel required was calculated by multiplying the cross section of the trench by the required length. Two lateral pipes, each 200 meters in length, consisting of 6-inch diameter nonperforated concrete pipe, would extend along two sides of the landfill and collect the flow from the perforated pipe sections.

For the C6a design, the surface (VP) layer and the lateral drainage layer would consist of 36 inches of soil, which is accounted for under item 23. For the D1b design, the lateral drainage layer would consist of 24 inches of sand. The cost is estimated under item 12 and includes hauling (within 20 miles), spreading, and compaction costs.

Item 13 estimates equipment and installation costs for a 1 horsepower, 4-inch submersible pump.

Item 14 estimates the cost for drilling a hole for the pump. The cost includes drilling and casing for a 15 cm diameter, 7 meter-deep hole.

For the A1 and B1c designs, there is no lateral drainage layer. However, for the A1 design, the cost of the surface (VP) layer is shown under item 11. This estimates the cost for a 6 inch gravel layer and includes labor costs for a dozer operator and a truck driver. Transportation costs are not included.

Gas Vents

Item 16 estimates costs for pipe vents to vent gases from the landfill. The cost is for 4 inch diameter, 30 foot long PVC pipe, perforated at one end. The estimate includes installation and casing costs, and an exhaust fan for each pipe vent.

Surface Water Control

Item 18 estimates the cost of constructing a drainage ditch to collect surface runoff from the landfill cover. The ditch is assumed to extend around the entire perimeter of the landfill. Also, a 100-meter section of ditch would lead from the edge of the landfill to a settling pond. The total length of the drainage ditch would be 900 meters. The ditch would be 1 meter wide by 0.5 meter deep.

Item 19 estimates the cost of constructing a settling pond with berm. This pond would allow sediment to settle out of the runoff from the landfill surface, before discharge to another water body; or, it could be used to store and evaporate the runoff. Pond design is based on a 5-cm 24-hour rainfall event, and assumes that water leaves the pond by evaporation and percolation, and that the land for the pond is already available. High and low costs shown are costs per hectare of landfill area.

Item 21 estimates the cost of maintaining the ditch twice per year.

Revegetation

Item 23 estimates the cost of soil material needed for the 24 inch surface (VP) layer for Cover Designs B1c and D1b. For Design C6a, item 23 shows the cost for a 36-inch combined VP and LD layer. The cost of the 6-inch gravel VP layer for Design A1 is accounted for under item 11 of Drainage Layer Installation.

Item 23a gives the cost estimate if topsoil is used for the surface layer. This estimate includes the cost of hauling (within 20 miles), spreading, and grading the topsoil.

Item 23b gives the cost estimate if local earth is used for the surface layer. The estimate includes the cost of on-site excavation, hauling (1,000- to 5,000-foot haul distance), spreading, and grading with a 300 horsepower dozer.

Items 24 and 25 estimate costs for hydroseeding with native grasses, and for mulching.

Item 28 estimates the cost for grass mowing for one year, assuming 6 mowings per year.

Item 29 estimates the cost for refertilization for one year.

SECTION 7

SUMMARY OF RESULTS

This report analyzes the hydrologic behavior of landfill cover designs solely in terms of average annual values of cover percolation, runoff, evapotranspiration, and lateral drainage for each design. Although the performance of a cover design during individual design storm events is also important, this type of analysis was beyond the scope of this report.

For the one-layer (Type B) covers, cover percolation is reduced as the soil type of the cover ranges from coarse textured (sandy) soils to fine textured (clayey) soils. Cover percolation for one-layer covers using a clay-loam soil (Type B1c) is less than 5 inches at 4 cities where average annual precipitation is less than 33 inches (Denver, San Francisco, Corpus Christi, and Milwaukee). For Type B1c, using "fair" grass instead of "excellent" grass results in a reduction in cover percolation ranging from 0 to 4 inches, and an increase in runoff ranging from 2 to 6 inches, for cities other than Denver. Cover percolation is increased slightly for Type B1c at Denver when fair grass is used instead of excellent grass.

For Type A (two-layer covers consisting of a gravel layer over a clay barrier), cover percolation is less than 1.7 inches for all 10 cities tested, when the gravel layer is 6 inches thick. Cover percolation is reduced when the gravel layer is reduced to 4 inches. Runoff is relatively high for this type, ranging from 1.6 to 24 inches for the 10 cities when the gravel layer is 6 inches thick.

For Types C1, C2, C3, and C5 (two-layer covers consisting of a topsoil layer over a clay barrier), cover percolation is slightly reduced as the soil texture of the topsoil layer ranges from coarse to fine. Cover peroclation is increased by 0.5 to 1.2 inches when thickness of the topsoil layer is increased from 24 to 48 inches. Cover percolation is reduced by approximately a factor of 10 when the hydraulic conductivity of the barrier layer is reduced by a factor of 10. Cover percolation is increased by 0.6 to 0.8 inches when the thickness of the barrier is reduced from 24 to 12 inches. The HELP Model results indicate that these cover types experience periodic saturation of the topsoil layer during the periods of record for the 10 cities tested (10 to 20 years). This condition could be harmful to the vegetative cover and could result in excessive surface runoff, depending on the frequency and persistence with which saturation occurs under a particular climatic regime. Further investigation of this phenomenon would be necessary to determine the suitability of these cover types for a given climate.

For Type C4, cover percolation is reduced 0.2 to 0.3 inches when a loamy sand, instead of a sandy loam, is used in the VP and LD layers. Increasing the total thickness of the VP and LD layers from 24 inches (Type C4a) to 36 inches (Type C6a) results in an increase in cover percolation from 0.0 to 0.1 inches for cities with less than 50 inches of annual precipitation; and an increase of 0.2 to 0.3 inches for cities with greater than 50 inches of annual precipitation.

For Type D (three layer covers), cover percolation is reduced by 0.25 to 0.55 inches when clay loam instead of sandy loam is used in the VP layer. The use of fair grass instead of excellent grass results in almost no difference in cover percolation for Type D1b. Changing the thickness of the VP layer from 12 inches to 24 inches results in almost no difference in cover percolation. Reducing the hydraulic conductivity of the lateral drainage layer by a factor of 8.4 results in a 0.5 to 0.9 inch reduction in cover percolation. Reducing the thickness of the lateral drainage layer results in almost no change in cover percolation. Cover percolation is reduced by 3 to 5 percent for every 1 percent increase in slope of the lateral drainage layer. Cover percolation is reduced by 3 to 9 percent for every 25 foot decrease in drainage spacing from 200 to 25 feet. Reducing the thickness of the barrier from 24 to 12 inches causes an increase in cover percolation from 0.2 to 0.03 inches. Reducing the hydraulic conductivity of the barrier layer by a factor of 10 significantly reduces cover percolation. The amount of the reduction depends on the initial value of the hydraulic conductivity and the precipitation at the site. For most of the cover designs examined in this study, a given level of cover percolation can be achieved by adjusting the hydraulic conductivity of the barrier layer.

Four other factors important in landfill cover design are animal and vector control, subsidence, gas control and cost.

Burrowing animals at landfill sites can be controlled by the use of dry, loose gravels and sands in the landfill cover to discourage tunneling. Birds and insects can be controlled by a sufficiently thick, compacted, well graded surface layer.

Techniques for controlling subsidence of landfill covers are still being developed and can be divided into two categories: (1) operations performed to control subsidence in the waste layer and (2) features of the cover layer which are intended to minimize the effects of subsidence. Examples of the first method are increasing the ratio of daily soil cover to waste, and compaction. An example of the second is the creation of a stable foundation or buffer layer between the base of the cover and the waste layer, consisting of 24 inches or more of compacted sand or gravel.

Control of methane gas and volatile toxic vapors at landfill sites are important considerations. Methane control techniques are designed to limit methane production and to control lateral subsurface migration by venting the gas to the atmosphere. With volatile toxics, both lateral migration and atmospheric emissions must be controlled. Some of the techniques for gas control are gas drainage layers with vents, vertical pipe vents, trench vents, and induced gas extraction systems. These techniques are discussed briefly in Section 5. References describing these techniques in more detail are listed in the bibliography.

Cost estimates for the four recommended cover types indicate that major expense items in landfill cover construction are material and installation costs for soil materials such as topsoil, sand and clay. Synthetic liners also are a major expense.

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APPENDIX A

APPENDIX A. COVER DESIGN DESCRIPTION

TYPE	LAYER	THICKNESS (inches)	SOIL #	SLOPE (%)	SPACING (feet)	VEGETATION	HYDRAULIC CONDUCTIVITY (in/hr)
A1	VP	6	1			none	
	B	12	20				
A2	VP	4	1			none	
	B	12	20				
B1a	VP	24	5			local grass	
B1b	VP	24	10			local grass	
B1c	VP	24	15			local grass	
B1c/f	VP	24	15			fair grass	
B1c/e	VP	24	15			excellent grass	
C1a	VP	24	5			local grass	
	B	24	20				
C1b	VP	24	10			local grass	
	B	24	20				
C1c	VP	24	15			local grass	
	B	24	20				
C2	VP	48	10			local grass	
	B	24	20				
C3	VP	24	10			local grass	
	B	12	20				
C4a	VP	ET	5			local grass	
	LD	24-ET	5	3	50		
	B	24	20				
C4e	VP	ET	10			local grass	
	LD	24-ET	10	3	50		
	B	24	20				
C5	VP	24	10			local grass	
	B	24	21				
C6a	VP	ET	5			local grass	
	LD	36-ET	5	3	50		
	B	24	20				
D1a	VP	24	5			local grass	
	LD	24	3	3	50		
	B	24	20				
D1b	VP	24	10			local grass	
	LD	24	3	3	50		6.620 in/hr
	B	24	20				0.000142 in/hr

APPENDIX A. COVER DESIGN DESCRIPTION

TYPE	LAYER	THICKNESS (inches)	SOIL #	SLOPE (%)	SPACING (feet)	VEGETATION	HYDRAULIC CONDUCTIVITY (in/hr)
D1b/f	VP	24	10			fair grass	
	LD	24	3	3	50		
	B	24	20				
D1b/e	VP	24	10			excellent grass	
	LD	24	3	3	50		
	B	24	20				
D1b/r	VP	24	10			local row crops	
	LD	24	3	3	50		
	B	24	20				
D1b/40	VP	24	10			local grass	
	LD	24	3	3	50	RCN=40	
	B	24	20				
D1b/90	VP	24	10			local grass	
	LD	24	3	3	50	RCN=90	
	B	24	20				
D1b3,x	VP	24	10			local grass	
	LD	24	3	3	x		
	B	24	20				
D1bx,50	VP	24	10			local grass	
	LD	24	3	x	50		
	B	24	20				
D1c	VP	24	10			local grass	
	LD	24	3	3	100		
	B	24	20				
D1d	VP	24	10			local grass	
	LD	24	3	6	50		
	B	24	20				
D1e	VP	24	10			local grass	
	LD	24	3	6	100		
	B	24	20				
D1f	VP	24	15			local grass	
	LD	24	3	3	50		
	B	24	20				
D2	VP	24	10			local grass	
	LD	12	3	3	50		
	B	24	20				
D3	VP	24	10			local grass	
	LD	24	3	3	50		
	B	12	20				

APPENDIX A. COVER DESIGN DESCRIPTION

TYPE	LAYER	THICKNESS (inches)	SOIL #	SLOPE (%)	SPACING (feet)	VEGETATION	HYDRAULIC CONDUCTIVITY (in/hr)
D4a	VP	24	10			local grass	
	LD	24	1	3	50		11.95 in/hr
	B	24	20				
D4b	VP	24	10			local grass	
	LD	24	M	3	50		1.417 in/hr
	B	24	20				
D5a	VP	24	10			local grass	
	LD	24	3	3	50		
	B	24	M				0.0142 in/hr
D5b	VP	24	10			local grass	
	LD	24	3	3	50		
	B	24	M				0.00142 in/hr
D5c	VP	24	10			local grass	
	LD	24	3	3	50		
	B	24	21				0.0000142 in/hr
D6	VP	12	10			local grass	
	LD	24	3	3	50		
	B	24	20				

"M" indicates that soil characteristics were manually inputted

APPENDIX B

COVER TYPE	CITY	ANNUAL PRECIPITATION	ANNUAL RUNOFF	EVAPO-TRANSPIRATION	COVER PERCOLATION	LATERAL DRAINAGE	MAX DAILY HEAD	MAXIMUM SATURATION
A1	DCO	14.93	1.592	12.105	1.1901		6.2	6
A1	SFCA	19.73	7.754	10.93	0.9982		6.2	6
A1	CCTX	30.5	10.461	18.646	1.3789		6.2	6
A1	MWC	33.07	8.751	22.699	1.3891		6.2	6
A1	SWA	34.98	18.56	14.787	1.573		6.2	6
A1	MNJ	40.66	13.674	25.478	1.4543		6.3	6
A1	LKY	42.11	12.597	27.921	1.5955		6.2	6
A1	HTX	49.48	18.948	28.842	1.5856		6.4	6
A1	CSC	51.69	19.959	30.053	1.6256		6.2	6
A1	NOLA	56.69	24.286	30.87	1.4723		6.5	6
A2	DCO	14.93	1.993	12.34	0.5736		4.2	4
A2	SFCA	19.73	8.391	10.77	0.539		4.2	4
A2	CCTX	30.5	11.058	18.773	0.6725		4.3	4
A2	MWC	33.07	9.133	22.797	0.9431		4.2	4
A2	SWA	34.98	19.122	14.824	0.9913		4.2	4
A2	MNJ	40.66	13.938	25.564	1.1214		4.3	4
A2	LKY	42.11	13.191	27.939	0.9956		4.2	4
A2	HTX	49.48	19.654	28.861	0.893		4.4	4
A2	CSC	51.69	20.518	30.096	1.0415		4.3	4
A2	NOLA	56.69	24.549	31.061	1.0365		4.5	4
B1a	DCO	14.93	0.069	8.654	6.2272			
B1a	SFCA	19.73	0.017	7.584	12.1497			
B1a	CCTX	30.5	0.501	11.904	18.1216			
B1a	MWC	33.07	0.009	16.587	16.3893			
B1a	SWA	34.98	0.009	11.515	23.4336			
B1a	MNJ	40.66	0.141	15.13	25.4254			
B1a	LKY	42.11	0.075	17.162	24.945			
B1a	HTX	49.48	0.001	18.803	30.733			
B1a	CSC	51.69	0	18.856	32.8732	0		
B1a	NOLA	56.69	0.007	18.938	37.7518			
B1b	DCO	14.93	0.285	11.61	3.018			
B1b	SFCA	19.73	0.222	10.87	8.6194			
B1b	CCTX	30.5	1.679	18.232	10.619			
B1b	MWC	33.07	0.241	22.178	10.5171			
B1b	SWA	34.98	0.233	14.021	20.6826			
B1b	MNJ	40.66	0.742	23.967	15.9542			
B1b	LKY	42.11	0.691	26.308	15.194			
B1b	HTX	49.48	0.442	30.87	18.1302			
B1b	CSC	51.69	0.088	31.356	20.2171			
B1b	NOLA	56.69	0.214	32.491	23.9282			
B1c	DCO	14.93	1.382	12.907	0.6176			
B1c	SFCA	19.73	2.788	12.227	4.683			
B1c	CCTX	30.5	6.257	21.445	2.8229			
B1c	MWC	33.07	2.75	25.379	4.7721			
B1c	SWA	34.98	3.766	15.897	15.2637			
B1c	MNJ	40.66	5.114	28.277	7.233			
B1c	LKY	42.11	5.327	30.366	6.5234			
B1c	HTX	49.48	4.791	37.496	7.0688			
B1c	CSC	51.69	3.541	38.141	9.9355			
B1c	NOLA	56.69	5.136	39.559	11.9185			

COVER TYPE	CITY	ANNUAL PRECIPITATION	ANNUAL RUNOFF	EVAPO-TRANSPIRATION	COVER PERCOLATION	LATERAL DRAINAGE	MAX DAILY HEAD	MAXIMUM SATURATION
Series of B1c runs with fair grass								
B1c/f	DCO	14.93	0.836	13.545	0.5182			
B1c/f	SFCA	19.73	2.788	12.227	4.683			
B1c/f	CCTX	30.5	6.257	21.445	2.8229			
B1c/f	MWC	33.07	2.704	24.817	5.3531			
B1c/f	SWA	34.98	3.686	15.709	15.5447			
B1c/f	NNJ	40.66	4.817	28.128	7.6832			
B1c/f	LKY	42.11	5.048	30.321	6.8167			
B1c/f	HTX	49.48	10.308	33.196	5.8978			
B1c/f	CSC	51.69	8.813	34.835	7.9949			
B1c/f	NOLA	56.69	11.349	35.535	9.7583			
Series of B1c runs with excellent grass								
B1c/e	DCO	14.93	0.246	14.454	0.2257			
B1c/e	SFCA	19.73	0.972	13.218	5.4743			
B1c/e	CCTX	30.5	3.016	24.26	3.2921			
B1c/e	MWC	33.07	0.832	26.562	5.5259			
B1c/e	SWA	34.98	1.132	16.275	17.5035			
B1c/e	NNJ	40.66	1.772	29.399	9.4418			
B1c/e	LKY	42.11	1.924	31.431	8.8912			
B1c/e	HTX	49.48	4.791	37.496	7.0688			
B1c/e	CSC	51.69	3.541	38.141	9.9355			
B1c/e	NOLA	56.69	5.136	39.559	11.9185			
C1a	DCO	14.93	0.363	12.223	2.1232		24.1	24
C1a	SFCA	19.73	4.038	13.315	2.0715		24.2	24
C1a	CCTX	30.5	4.381	23.828	2.1324		24.3	24
C1a	MWC	33.07	3.026	27.656	1.9737		24.1	24
C1a	SWA	34.98	14.216	18.262	2.1426		24.1	24
C1a	NNJ	40.66	6.094	32.172	2.1938		24.3	24
C1a	LKY	42.11	5.682	34.168	2.0818		24.1	24
C1a	HTX	49.48	4.272	42.603	1.9756		24.4	24
C1a	NOLA	56.69	9.243	45.039	2.0382		24.5	24
C1b	DCO	14.93	0.41	12.371	1.9826		24	24
C1b	SFCA	19.73	3.805	13.659	2.0121		24.3	24
C1b	CCTX	30.5	4.758	23.557	2.0722		24.1	24
C1b	MWC	33.07	3.27	27.5	1.9465		24.2	24
C1b	SWA	34.98	14.734	17.843	2.1089		24.1	24
C1b	NNJ	40.66	6.527	31.818	2.1637		24.1	24
C1b	LKY	42.11	6.192	33.764	2.0536		24.1	24
C1b	HTX	49.48	4.433	42.641	1.9146		24.1	24
C1b	CSC	51.69	6.785	42.765	1.9739		24.2	
C1b	NOLA	56.69	9.606	44.77	2.0071		24.3	24
C1c	DCO	14.93	1.383	12.861	0.6455		18.5	24
C1c	SFCA	19.73	5.409	12.474	1.7353		24	24
C1c	CCTX	30.5	7.211	21.701	1.5977		24	24
C1c	MWC	33.07	5.164	26.193	1.5285		24	24
C1c	SWA	34.98	16.294	16.592	1.9408		24	24
C1c	NNJ	40.66	9.382	29.263	1.9718		24	24
C1c	LKY	42.11	9.096	31.262	1.8556		24	24
C1c	HTX	49.48	8.154	39.426	1.6421		24	24
C1c	CSC	51.69	9.707	40.102	1.776		24.1	24
C1c	NOLA	56.69	12.931	41.748	1.8413		24.1	24

COVER TYPE	CITY	ANNUAL PRECIPITATION	ANNUAL RUNOFF	EVAPO- TRANSPIRATION	COVER PERCOLATION	LATERAL DRAINAGE	MAX DAILY HEAD	MAXIMUM SATURATION
C2	DCO	14.93	0.361	11.784	2.5434		41.6	48
C2	SFCA	19.73	2.951	13.218	3.0957		48.2	48
C2	CCTX	30.5	4.5	22.432	3.2105		48.2	48
C2	MWC	33.07	2.575	26.692	3.0178		48.1	48
C2	NNJ	40.66	5.805	31.071	3.3929		48.1	48
C2	NOLA	56.69	9.036	43.857	3.239		48.4	48
C3	DCO	14.93	0.363	12.043	2.4179		23.5	24
C3	SFCA	19.73	3.413	13.424	2.6569		24.2	24
C3	CCTX	30.5	4.629	22.946	2.8139		24.2	24
C3	MWC	33.07	2.953	27.222	2.552		24.1	24
C3	NNJ	40.66	6.025	31.51	2.9778		24.1	24
C3	NOLA	56.69	9.244	44.472	2.6678		24.4	24
C4a	DCO	14.93	0.112	8.871	1.3496	4.582	14.9	24
C4a	SFCA	19.73	0.027	8.385	1.3548	9.824	23.1	24
C4a	CCTX	30.5	1.174	13.483	1.6012	14.198	24.4	24
C4a	MWC	33.07	0.018	18.67	1.5319	12.667	22	24
C4a	SWA	34.98	0.055	12.035	1.6301	21.033	22.8	24
C4a	NNJ	40.66	0.265	19.094	1.6992	19.539	23.7	24
C4a	LKY	42.11	0.142	21.421	1.6621	18.891	22.6	24
C4a	HTX	49.48	0.3	27.815	1.584	19.593	24.1	24
C4a	CSC	51.69	0	29.615	1.6019	20.354	21.8	24
C4a	NOLA	56.69	0.13	30.709	1.6261	24.014	22.2	24
C4e	DCO	14.93	0.36	11.74	1.539	1.235	17.7	24
C4e	SFCA	19.73	1.891	12.472	1.7948	3.378	24.1	24
C4e	CCTX	30.5	3.812	20.641	1.9	4.054	24.3	24
C4e	MWC	33.07	1.519	25.529	1.7767	3.94	24	24
C4e	SWA	34.98	7.716	16.063	1.9647	8.944	24.1	24
C4e	NNJ	40.66	2.023	28.871	2.0048	7.643	24	24
C4e	LKY	42.11	2.17	31.275	1.9215	6.68	24	24
C4e	HTX	49.48	1.823	39.111	1.7767	6.451	24.2	24
C4e	CSC	51.69	1.945	39.897	1.8488	7.85	24.3	24
C4e	NOLA	56.69	4.338	41.572	1.8754	8.606	24.2	24
C5	DCO	14.93	0.59	13.896	0.2184		24.1	24
C5	SWA	34.98	16.104	18.351	0.2312		24.1	24
C5	NNJ	40.66	7.578	32.645	0.2664		24.1	24
C5	NOLA	56.69	10.519	45.62	0.2437		24.3	24
C6a	DCO	14.93	0.112	8.879	1.3491	4.575	14.9	36
C6a	SFCA	19.73	0.023	7.95	1.3769	10.241	27.1	36
C6a	CCTX	30.5	0.892	12.482	1.6324	15.451	34.5	36
C6a	MWC	33.07	0.018	17.07	1.584	14.211	26.5	36
C6a	SWA	34.98	0.015	11.872	1.7205	21.068	30.4	36
C6a	NNJ	40.66	0.232	16.021	1.7938	22.545	31	36
C6a	LKY	42.11	0.115	18.062	1.7584	22.181	26.6	36
C6a	HTX	49.48	0.0004	21.198	1.8295	26.169	32.9	36
C6a	CSC	51.69	0	21.53	1.8686	28.142	30	36
C6a	NOLA	56.69	0.068	21.977	1.9209	32.439	33.5	36

COVER TYPE	CITY	ANNUAL PRECIPITATION	ANNUAL RUNOFF	EVAPO-TRANSPIRATION	COVER PERCOLATION	LATERAL DRAINAGE	MAX DAILY HEAD	MAXIMUM SATURATION
D1a	DCO	14.93	0.105	8.856	1.0097	4.968	16.2	48
D1a	SFCA	19.73	0.021	7.898	0.8901	10.847	24.6	48
D1a	CCTX	30.5	0.676	12.376	1.3414	16.122	39.2	48
D1a	MWC	33.07	0.016	17.009	1.153	14.798	24.4	48
D1a	SWA	34.98	0.013	11.842	1.3976	21.584	27.4	48
D1a	NNJ	40.66	0.216	15.9	1.5268	23.02	26.8	48
D1a	LKY	42.11	0.105	17.897	1.4939	22.687	27.5	48
D1a	HTX	49.48	0.003	19.965	1.5561	27.839	32.3	48
D1a	CSC	51.69	0	19.978	1.5871	30.056	28.3	48
D1a	NOLA	56.69	0.014	20.183	1.6279	34.711	36.1	48
D1b	DCO	14.93	0.356	11.748	0.796	2.008	11.2	48
D1b	SFCA	19.73	0.291	11.223	0.7868	7.339	21.5	48
D1b	CCTX	30.5	2.037	18.645	1.1791	8.655	35.6	48
D1b	MWC	33.07	0.316	22.672	1.0565	8.89	26.1	48
D1b	SWA	34.98	0.321	14.365	1.281	18.843	27.5	48
D1b	NNJ	40.66	0.98	24.92	1.4406	13.308	21.9	48
D1b	LKY	42.11	0.876	27.222	1.3973	12.699	22.9	48
D1b	HTX	49.48	0.704	32.267	1.4417	14.952	33.3	48
D1b	CSC	51.69	0.16	32.91	1.4899	17.053	28	48
D1b	NOLA	56.69	0.358	34.297	1.5245	20.333	29.5	48
Series of D1b Runs with Fair Grass								
D1b/f	DCO	14.93	0.168	11.876	0.8231	2.049	11.3	48
D1b/f	SFCA	19.73	0.291	11.223	0.786	7.339	21.5	48
D1b/f	CCTX	30.5	2.037	18.645	1.179	8.655	35.6	48
D1b/f	MWC	33.07	0.263	22.232	1.058	9.371	26.4	48
D1b/f	SWA	34.98	0.259	14.361	1.275	18.926	27.8	48
D1b/f	NNJ	40.66	0.857	24.967	1.439	13.389	23.7	48
D1b/f	LKY	42.11	0.764	27.228	1.4004	12.778	23	48
D1b/f	HTX	49.48	3.165	29.352	1.4406	15.397	29.4	48
D1b/f	CSC	51.69	1.89	30.668	1.484	17.562	25.4	48
D1b/f	NOLA	56.69	2.682	31.461	1.515	20.868	27.6	48
Series of D1b Runs with Excellent Grass								
D1b/e	DCO	14.93	0	12.422	0.799	1.715	9.5	
D1b/e	SFCA	19.73	0.014	11.9	0.7804	6.942	21.9	
D1b/e	CCTX	30.5	0.389	20.563	1.1707	8.428	45.5	
D1b/e	MWC	33.07	0.006	23.261	1.0526	8.624	26.5	
D1b/e	SWA	34.98	0.003	14.682	1.2785	18.833	29.6	
D1b/e	NNJ	40.66	0.072	25.417	1.4525	13.694	24.8	
D1b/e	LKY	42.11	0.048	27.521	1.4046	13.243	27.2	
D1b/e	HTX	49.48	0.704	32.267	1.4417	14.952	33.3	48
D1b/e	CSC	51.69	0.16	32.91	1.4899	17.053	28	48
D1b/e	NOLA	56.69	0.358	34.297	1.5245	20.333	29.5	48
Series of D1b runs with Row Crops								
D1b/r	DCO	14.93	0.475	12.807	0.5834	1.037	9.9	48
D1b/r	SFCA	19.73	1.109	11.653	0.704	6.171	20.1	48
D1b/r	CCTX	30.5	4.182	19.537	1.003	5.808	26.8	48
D1b/r	MWC	33.07	0.04	24.86	0.9321	7.077	27.2	48
D1b/r	SWA	34.98	0.047	15.974	1.1161	17.67	29.1	48
D1b/r	NNJ	40.66	0.3	29.202	1.3661	9.775	24.4	48
D1b/r	LKY	42.11	0.249	31.252	1.3034	9.39	24.9	48
D1b/r	HTX	49.48	1.576	34.094	1.3598	12.341	33.5	48
D1b/r	CSC	51.69	0.659	34.652	1.42	14.868	28.6	48
D1b/r	NOLA	56.69	1.072	36.202	1.4741	17.756	29.7	48

COVER TYPE	CITY	ANNUAL PRECIPITATION	ANNUAL RUNOFF	EVAPO- TRANSPIRATION	COVER PERCOLATION	LATERAL DRAINAGE	MAX DAILY HEAD	MAXIMUM SATURATION
Series of D1b runs with a Runoff Curve Number of 90								
D1b/90	DCO	14.93	0.96	11.517	0.7863	1.645	8.5	48
D1b/90	SFCA	19.73	2.246	10.766	0.761	5.87	18.1	48
D1b/90	CCTX	30.5	6.406	17.482	1.1202	5.519	20	48
D1b/90	MWC	33.07	2.369	21.97	1.0347	7.562	22.5	48
D1b/90	SWA	34.98	2.546	14.151	1.2521	16.867	22.1	48
D1b/90	NNJ	40.66	4.756	23.633	1.3949	10.877	14.7	48
D1b/90	LKY	42.11	4.77	25.882	1.3563	10.185	15.1	48
D1b/90	HTX	49.48	10.131	29.055	1.3564	8.884	12	48
D1b/90	CSC	51.69	8.817	29.832	1.406	11.569	16.1	48
D1b/90	NOLA	56.69	11.025	30.935	1.4236	13.188	17.6	48
Series of D1b runs with a Runoff Curve Number of 40								
D1b/40	DCO	14.93	0	11.851	0.7987	2.258	16.4	48
D1b/40	SFCA	19.73	0	11.275	0.79	7.57	24	48
D1b/40	CCTX	30.5	0.099	19.054	1.1996	10.174	48.2	48
D1b/40	MWC	33.07	0	22.748	1.0603	9.127	26.7	48
D1b/40	SWA	34.98	0	14.388	1.2852	19.135	29.9	48
D1b/40	NNJ	40.66	0	25.194	1.4524	14	28.4	48
D1b/40	LKY	42.11	0	27.429	1.4065	13.358	27.2	48
D1b/40	HTX	49.48	0.033	32.423	1.4483	15.459	34.5	48
D1b/40	CSC	51.69	0	32.964	1.4915	17.158	28.2	48
D1b/40	NOLA	56.69	0.033	34.365	1.5279	20.584	36	48
Series of D1b runs at LKY with drain spacing from 25 to 200 feet, slope 3 percent								spacing
D1b3,25		42.11	0.849	27.223	1.2669	12.855	17	25
D1b3,50		42.11	0.876	27.222	1.3973	12.699	22.9	50
D1b3,75		42.11	0.886	27.222	1.4874	12.598	26	75
D1b3,100		42.11	0.892	27.217	1.5633	12.519	27.7	100
D1b3,125		42.11	0.895	27.236	1.6336	12.42	28.9	125
D1b3,150		42.11	0.897	27.253	1.7003	12.327	29.9	150
D1b3,175		42.11	0.899	27.261	1.7631	12.248	30.9	175
D1b3,200		42.11	0.9	27.265	1.8223	12.176	32.1	200
Series of D1b runs at LKY with drain spacing from 200 to 2000 feet, slope 3 percent								
D1b3,200		42.11	0.9	27.265	1.8223	12.176	32.1	200
D1b3,400		42.11	0.905	27.367	2.2208	11.602	41.4	400
D1b3,600		42.11	0.921	27.959	2.4888	10.653	47.6	600
D1b3,800		42.11	1.045	28.577	2.6377	9.714	47.8	800
D1b3,1000		42.11	1.204	28.976	2.7365	9.021	48.1	1000
D1b3,1200		42.11	1.363	29.241	2.7997	8.508	48.1	1200
D1b3,1400		42.11	1.482	29.461	2.8402	8.108	48.1	1400
D1b3,1600		42.11	1.588	29.631	2.8667	7.79	48.1	1600
D1b3,1800		42.11	1.685	29.759	2.8847	7.536	48.1	1800
D1b3,2000		42.11	1.758	29.855	2.9026	7.339	48.1	2000

COVER TYPE	CITY	ANNUAL PRECIPITATION	ANNUAL RUNOFF	EVAPO-TRANSPIRATION	COVER PERCOLATION	LATERAL DRAINAGE	MAX DAILY HEAD	MAXIMUM SATURATION
Series of D1b runs at LKY with slopes from 0 percent to 10 percent, spacing 50 feet								Slope
D1b0,50		42.11	0.881	27.226	1.6109	12.438	27.3	0%
D1b1,50		42.11	0.881	27.223	1.5299	12.55	25.7	1%
D1b2,50		42.11	0.879	27.226	1.458	12.631	24.1	2%
D1b3,50		42.11	0.876	27.222	1.3973	12.699	22.9	3%
D1b4,50		42.11	0.872	27.219	1.3521	12.751	21.8	4%
D1b5,50		42.11	0.867	27.204	1.3093	12.812	20.7	5%
D1b6,50		42.11	0.863	27.202	1.2709	12.858	19.8	6%
D1b7,50		42.11	0.858	27.202	1.2351	12.898	18.9	7%
D1b8,50		42.11	0.854	27.198	1.1995	12.942	19.1	8%
D1b9,50		42.11	0.85	27.197	1.1664	12.981	18.2	9%
D1b10,50		42.11	0.845	27.193	1.1355	13.02	17.5	10%
D1c	DCO	14.93	0.358	11.751	0.9497	1.844	13.4	48
D1c	SFCA	19.73	0.298	11.2	1.015	7.106	30.3	48
D1c	CCTX	30.5	2.051	18.677	1.39	8.397	45.6	48
D1c	MWC	33.07	0.326	22.668	1.266	8.659	38.3	48
D1c	NNJ	40.66	0.994	24.964	1.6093	13.068	29.5	48
D1c	HTX	49.48	0.727	32.264	1.6311	14.702	41.4	48
D1c	NOLA	56.69	0.375	34.366	1.7582	19.953	41.8	48
D1d	DCO	14.93	0.352	11.731	0.6394	2.189	10.5	48
D1d	SFCA	19.73	0.284	11.22	0.6433	7.513	19.1	48
D1d	CCTX	30.5	2.02	18.622	0.9463	8.942	31	48
D1d	MWC	33.07	0.31	22.677	0.9145	9.034	21.6	48
D1d	NNJ	40.66	0.966	24.973	1.3251	13.492	19.1	48
D1d	NOLA	56.69	0.346	34.131	1.3822	20.674	27.2	48
D1e	DCO	14.93	0.356	11.745	0.7633	2.045	11.3	48
D1e	SFCA	19.73	0.292	11.214	0.7721	7.358	23.8	48
D1e	CCTX	30.5	2.04	18.648	1.1508	8.689	39.3	48
D1e	MWC	33.07	0.318	22.66	1.0406	8.917	32	48
D1e	NNJ	40.66	0.984	24.923	1.4337	13.31	22.8	48
D1e	NOLA	56.69	0.366	34.277	1.5374	20.32	35.1	48
D1f	DCO	14.93	1.385	12.873	0.2572	0.385	4	48
D1f	SFCA	19.73	2.916	12.051	0.5475	4.144	15.8	48
D1f	CCTX	30.5	6.36	21.205	0.6039	2.359	13.2	48
D1f	MWC	33.07	2.863	25.316	0.5998	4.121	20.3	48
D1f	SWA	34.98	4.124	15.848	0.9082	13.929	18.5	48
D1f	NNJ	40.66	5.474	28.233	0.9827	5.928	11.5	48
D1f	LKY	42.11	5.618	30.307	0.9085	5.382	12.1	48
D1f	HTX	49.48	5.126	37.582	0.9451	5.616	17.1	48
D1f	CSC	51.69	3.943	38.363	1.0101	8.273	17.5	48
D1f	NOLA	56.69	5.644	39.739	1.1087	10.023	19.6	48

COVER TYPE	CITY	ANNUAL PRECIPITATION	ANNUAL RUNOFF	EVAPO- TRANSPIRATION	COVER PERCOLATION	LATERAL DRAINAGE	MAX DAILY HEAD	MAXIMUM SATURATION
Type D2 is a D1b with a 12 inch LD layer								
D2	DCO	14.93	0.356	11.742	0.7947	2.016	11.2	36
D2	SFCA	19.73	0.291	11.213	0.7904	7.344	22.9	36
D2	CCTX	30.5	2.071	18.616	1.1834	8.656	34.5	36
D2	MWC	33.07	0.319	22.661	1.0604	8.895	30.3	36
D2	SWA	34.98	0.325	14.354	1.2941	18.804	28.8	36
D2	NNJ	40.66	0.981	24.903	1.4418	13.324	21.9	36
D2	LKY	42.11	0.878	27.212	1.3987	12.705	22.9	36
D2	HTX	49.48	0.716	32.294	1.4471	14.909	34.3	36
D2	CSC	51.69	0.162	32.884	1.4946	17.074	29.6	36
D2	NOLA	56.69	0.365	34.258	1.5352	20.343	33.2	36
Type D3 is a D1b with a 12 inch barrier layer								
D3	DCO	14.93	0.356	11.747	0.8224	1.983	11.2	48
D3	SFCA	19.73	0.291	11.219	0.8714	7.258	21.5	48
D3	CCTX	30.5	2.037	18.643	1.2816	8.565	35.5	48
D3	MWC	33.07	0.316	22.672	1.1629	8.784	26	48
D3	SWA	34.98	0.32	14.365	1.4811	18.643	27.4	48
D3	NNJ	40.66	0.98	24.919	1.6118	13.138	21.8	48
D3	LKY	42.11	0.876	27.222	1.5592	12.537	22.9	48
D3	HTX	49.48	0.703	32.267	1.6223	14.772	33.2	48
D3	CSC	51.69	0.16	32.907	1.6951	16.852	27.9	48
D3	NOLA	56.69	0.358	34.286	1.7592	20.11	29.4	48
Type D4a is a D1b with soil #1 in the LD layer (H.C.=11.95 in/hr)								
D4a	DCO	14.93	0.352	11.732	0.6571	2.17	11.732	48
D4a	SFCA	19.73	0.283	11.231	0.6549	7.495	19.6	48
D4a	CCTX	30.5	2.016	18.644	0.9672	8.903	29.9	48
D4a	MWC	33.07	0.308	22.684	0.9277	9.017	21.1	48
D4a	SWA	34.98	0.309	14.363	1.1196	19.072	22.5	48
D4a	NNJ	40.66	0.963	24.876	1.3395	13.477	19.3	48
D4a	LKY	42.11	0.858	27.208	1.2864	12.841	20	48
D4a	HTX	49.48	0.674	32.205	1.3062	15.199	28.3	48
D4a	CSC	51.69	0.152	32.83	1.3678	17.275	23	48
D4a	NOLA	56.69	0.339	34.142	1.3957	20.667	27.9	48
Type D4b is a D1b with an LD layer hydraulic conductivity of 1.417 in/hr (.001 cm/sec)								
D4b	DCO	14.93	0.36	11.751	1.2509	1.531	12.2	
D4b	SFCA	19.73	0.304	11.282	1.5407	6.449	30.4	
D4b	CCTX	30.5	2.06	18.656	1.6447	8.098	42.8	
D4b	MWC	33.07	0.334	22.682	1.6315	8.168	36	
D4b	SWA	34.98	0.351	14.42	1.9254	17.874	43.3	
D4b	NNJ	40.66	1.002	25.037	1.8565	12.681	32.5	
D4b	LKY	42.11	0.9	27.264	1.8044	12.138	26.9	
D4b	HTX	49.48	0.736	32.29	1.8856	14.243	42.7	
D4b	CSC	51.69	0.172	33.031	1.9644	16.359	43.7	
D4b	NOLA	56.69	0.383	34.435	2.0456	19.462	47.5	

COVER TYPE	CITY	ANNUAL PRECIPITATION	ANNUAL RUNOFF	EVAPO-TRANSPIRATION	COVER PERCOLATION	LATERAL DRAINAGE	MAX DAILY HEAD	MAXIMUM SATURATION
Type D5a is a D1b with a B layer hydraulic conductivity of 0.0142 in/hr (.00001 cm/sec)								
D5a	DCO	14.93	0.318	11.665	2.8936	0.037	6.1	48
D5a	SFCA	19.73	0.251	10.999	8.1235	0.337	13.8	48
D5a	CCTX	30.5	1.888	18.475	9.5726	0.594	22.8	48
D5a	MWC	33.07	0.278	22.383	9.9966	0.273	10.4	48
D5a	SWA	34.98	0.277	14.138	19.8306	0.692	12.8	48
D5a	MNJ	40.66	0.854	24.357	15.1268	0.321	12.1	48
D5a	LKY	42.11	0.775	26.699	14.3618	0.358	12.4	48
D5a	HTX	49.48	0.626	31.472	16.3278	0.988	21.9	48
D5a	CSC	51.69	0.128	31.995	18.7728	0.761	15.5	48
D5a	NOLA	56.69	0.303	33.244	21.7874	1.283	22.9	48
Type D5b is a D1b with a B layer hydraulic conductivity of 0.00142 in/hr (.000001 cm/sec)								
D5b	DCO	14.93	0.351	11.703	2.2534	0.607	10.5	48
D5b	SFCA	19.73	0.287	11.152	4.1366	4.08	19.8	48
D5b	CCTX	30.5	2.025	18.578	5.4064	4.52	33.4	48
D5b	MWC	33.07	0.313	22.606	5.5996	4.418	24.1	48
D5b	SWA	34.98	0.32	14.315	8.1106	12.083	25.5	48
D5b	MNJ	40.66	0.974	24.815	9.3634	5.512	19.8	48
D5b	LKY	42.11	0.871	27.122	8.7492	5.451	20.8	48
D5b	HTX	49.48	0.699	32.159	8.9651	7.569	31.2	48
D5b	CSC	51.69	0.159	32.778	9.9781	8.718	25.9	48
D5b	NOLA	56.69	0.356	34.11	10.7086	11.357	27.6	48
Type D5c is a D1b with a #21 barrier layer (H.C.=0.0000142 in/hr)								
D5c	DCO	14.93	0.356	11.752	0.1188	2.678	11.5	48
D5c	SFCA	19.73	0.291	11.221	0.1038	8.02	21.8	48
D5c	CCTX	30.5	2.037	18.638	0.1375	9.711	35.8	48
D5c	MWC	33.07	0.316	22.674	0.1223	9.816	26.3	48
D5c	SWA	34.98	0.32	14.368	0.1479	19.971	27.7	48
D5c	MNJ	40.66	0.98	24.919	0.1464	14.6	22.2	48
D5c	LKY	42.11	0.876	27.223	0.1427	13.95	23.2	48
D5c	HTX	49.48	0.703	32.267	0.1478	16.241	33.5	48
D5c	CSC	51.69	0.16	32.91	0.1509	18.39	28.2	48
D5c	NOLA	56.69	0.358	34.288	0.1542	21.71	29.7	48
Type D6 is a D1b with a 12 inch VP layer								
D6	DCO	14.93	0.354	11.73	0.8002	2.024	11.7	36
D6	SFCA	19.73	0.288	11.206	0.787	7.359	21.5	36
D6	CCTX	30.5	2.04	18.581	1.184	8.721	34.1	36
D6	MWC	33.07	0.313	22.187	1.0703	9.374	25.5	36
D6	SWA	34.98	0.317	14.262	1.297	18.935	27.4	36
D6	MNJ	40.66	0.97	24.311	1.446	13.933	21.5	36
D6	LKY	42.11	0.865	26.57	1.407	13.353	22	36
D6	HTX	49.48	0.686	28.932	1.477	18.278	33.5	36
D6	CSC	51.69	0.152	30.803	1.508	19.157	27.2	36
D6	NOLA	56.69	0.346	31.961	1.544	22.655	29.5	36

APPENDIX C

APPENDIX C
COST ESTIMATES FOR RECOMMENDED COVERS

					Type B1c		Type A1	
	Unit	lo	hi	average	units	cost	units	cost
Site preparation								
1. Excavating,grading, recontouring	m3	$1.58	$1.83	$1.71	20,000	$34,100	20,000	$34,100
2. Excavating,grading soil(0.3 m)	m3	$0.90	$1.05	$0.98	12,000	$11,700	12,000	$11,700
3. Total						$45,800		$45,800
Barrier Layer Installation								
4. Clay, Installed	m3			$11.11			12,192	$135,453
5. Total								$135,453
Synthetic Liner								
6. Liner, installed	m2	$4.35	$7.37	$5.86			40,000	$294,800
7. Total								$294,800
Drainage Layer Installation								
8. Trench Excavation	m3	$1.33	$1.51	$1.42				
9. 4" Perforated Pipe, Installed	m	$5.81	$9.31	$7.56				
10. 6" Cement Pipe, Installed	m	$7.03	$11.23	$9.13				
11. Gravel, Installed	m3	$7.10	$10.88	$8.99			6,096	$54,803
12. Sand, Installed	m3			$19.61				
13. Pump	ea	$550.00	$900.00	$725.00				
14. Drilled Hole for Pump	ea	$110.00	$180.00	$145.00				
15. Total								$54,803
Gas Vents								
16. Pipe Vents,Installed	ea			$1,110	8	$8,880	8	$8,880
17. Total						$8,880		$8,880
Surface Water Control								
18. Diversion Ditch	m3	$1.72	$3.61	$2.67	450	$1,199	450	$1,199
19. Settling Pond w/Berm	ha	$447.00	$708.00	$577.50	4	$2,310	4	$2,310
20. Subtotal						$3,509		$3,509
21. Ditch maintenance, twice per yr	m3	$3.44	$7.22	$5.33	450	$2,399	450	$2,399
22. Total (10 years)						$27,494		$27,494
Revegetation								
23. Soil (Select one)	m3							
a. Topsoil,installed	m3			$17.00	24,384	$414,528		
b. Local soil,installed	m3	$3.24	$4.70	$3.97	24,384	$96,804		
24. Hydroseeding	ha	$906.00	$1,275	$1,091	4	$4,362		
25. Mulching	ha	$268.00	$384.00	$326.00	4	$1,304		
26. Subtotal, with topsoil						$420,194		
27. Subtotal, with local soil						$102,470		
28. Grass mowing, six per yr	ha	$59.00	$120.00	$89.50	4	$358		
29. Refertilization, once per yr	ha	$46.00	$65.00	$55.50	4	$222		
30. Total (10 years), topsoil						$425,994		
31. Total (10 years), local soil						$108,270		
Grand Total, with Topsoil						$508,168		$567,230
Grand Total, with Local Soil						$190,445		$567,230

	Unit	Type C6a		Type D1b		Source
		units	cost	units	cost	
Site preparation						
1. Excavating,grading, recontouring	m3	20,000	$34,100	20,000	$34,100	Rishel et al,1982
2. Excavating,grading soil(0.3 m)	m3	12,000	$11,700	12,000	$11,700	Rishel et al,1982
3. Total			$45,800		$45,800	
Barrier Layer Installation						
4. Clay, Installed	m3	24,384	$270,906	24,384	$270,906	EPA, 1985
5. Total			$270,906		$270,906	
Synthetic Liner						
6. Liner, installed	m2					Rishel et al,1982
7. Total						
Drainage Layer Installation						
8. Trench Excavation	m3	250	$355	250	$355	Rishel et al,1982
9. 4" Perforated Pipe, Installed	m	2,800	$21,168	2,800	$21,168	Rishel et al,1982
10. 6" Cement Pipe, Installed	m	400	$3,652	400	$3,652	Rishel et al,1982
11. Gravel, Installed	m3	250	$2,248	250	$2,248	Rishel et al,1982
12. Sand, Installed	m3			24,384	$478,170	EPA,1985
13. Pump	ea	1	$725	1	$725	Rishel et al,1982
14. Drilled Hole for Pump	ea	1	$145	1	$145	Rishel et al,1982
15. Total			$28,293		$506,463	
Gas Vents						
16. Pipe Vents,Installed	ea	8	$8,880	8	$8,880	EPA,1985
17. Total			$8,880		$8,880	
Surface Water Control						
18. Diversion Ditch	m3	450	$1,199	450	$1,199	Rishel et al,1982
19. Settling Pond w/Berm	ha	4	$2,310	4	$2,310	Rishel et al,1982
20. Subtotal			$3,509		$3,509	
21. Ditch maintenance twice per yr	m3	450	$2,399	450	$2,399	Rishel et al,1982
22. Total (10 years)			$27,494		$27,494	
Revegetation						
23. Soil (Select one)	m3					
a. Topsoil,installed	m3	36,576	$621,792	24,384	$414,528	EPA,1985
b. Local soil,installed	m3	36,576	$145,207	24,384	$96,804	EPA,1985
24. Hydroseeding	ha	4	$4,362	4	$4,362	Rishel et al,1982
25. Mulching	ha	4	$1,304	4	$1,304	Rishel et al,1982
26. Subtotal, with topsoil			$627,458		$420,194	
27. Subtotal, with local soil			$150,873		$102,470	
28. Grass mowing, six per yr	ha	4	$358	4	$358	Rishel et al,1982
29. Refertilization, once per yr	ha	4	$222	4	$222	Rishel et al,1982
30. Total (10 years), topsoil			$633,258		$425,994	
31. Total (10 years), local soil			$156,673		$108,270	
Grand Total, with Topsoil			$1,014,631		$1,285,537	
Grand Total, with Local Soil			$538,046		$967,814	

APPENDIX D

APPENDIX D
SAMPLE STANDARD DEVIATIONS OF WATER BALANCE COMPONENTS
COVER TYPES B1C AND D1B

COVER TYPE	CITY	PRECIPITATION	RUNOFF	EVAPO-TRANSPIRATION	COVER PERCOLATION	LATERAL DRAINAGE
B1c	DCO	4.446	1.159	3.005	0.705	
B1c	SFCA	6.075	1.712	2.524	2.777	
B1c	CCTX	9.427	3.759	5.006	1.995	
B1c	MWC	4.254	1.268	3.587	2.107	
B1c	SWA	6.092	1.286	1.982	3.683	
B1c	NNJ	7.669	3.023	3.724	2.204	
B1c	LKY	6.785	2.699	3.879	2.594	
B1c	HTX	9.821	2.651	5.841	3.32	
B1c	CSC	10.084	2.361	4.385	4.505	
B1c	NOLA	11.487	2.778	4.882	5.435	
D1b	DCO	4.446	0.459	2.686	0.188	1.348
D1b	SFCA	6.075	0.385	2.311	0.103	3.73
D1b	CCTX	9.427	1.642	4.371	0.178	4.182
D1b	MWC	4.254	0.283	3.147	0.043	2.745
D1b	SWA	6.092	0.276	1.869	0.098	3.868
D1b	NNJ	7.669	1.236	3.231	0.054	4.058
D1b	LKY	6.785	0.91	3.617	0.11	3.439
D1b	HTX	9.821	0.996	4.865	0.063	5.23
D1b	CSC	10.084	0.275	4.414	0.066	6.238
D1b	NOLA	11.487	0.629	4.745	0.066	7.008

APPENDIX E

APPENDIX E

Glossary

DEFAULT VALUE: A value supplied by the HELP Model computer program when the user chooses not to supply a value.

FIELD CAPACITY: The maximum amount of moisture a soil or solid waste can retain in a gravitational field without a continuous downward percolation. (EPA, In Press)

HYDRAULIC CONDUCTIVITY: The rate of discharge of water under laminar-flow conditions and at a standard temperature (usually 20 degrees C) through a unit cross-sectional area of a porous medium under a unit hydraulic gradient. Used interchangeably with permeability in this report. (EPA, In Press)

LOCAL GRASS: The grass type (shown in Table 2) that was specified for a particular city when running the HELP Model for some of the cover types used in this report. It represents an estimate of the stand of grass that would occur naturally under the climatic conditions for that city.

PERMEABILITY: Capability of a material to transmit fluid through its substance. Used interchangeably with hydraulic conductivity in this report. (EPA, In Press)

WILTING POINT: The moisture content of the soil at which plants wilt and fail to recover their turgidity. (Brady, 1974).

HELP - : Hydraulic Evaluation of Landfill Performance Model, a computer model developed for the U.S. Environmental Protection Agency.